Sustainable supply chains

Bridging the gap between environmental economics and operations management

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Rôlje, rôlje, wetterweagen
Rôlje en brûs om ‘t âlde Grou
Miriaden foar ús eagen
Fleagen, stauwen om ús Grou
Rôlje, rôlje ús foarby
Hurde Friezen bliuwe wy
Hurde Friezen bliuwe wy

Foar myn Pake en Beppe

Declaration

I hereby declare that except where specific reference is made to the work of others in this statement, the contents of this dissertation are the result of my own work and have not been submitted, or, are being concurrently submitted in whole or in part for consideration for any other degree or qualification at the University of Cambridge, or any other university. This dissertation contains fewer than 80,000 words and complies with the guidelines on length and format.

Chapter 2 is the outcome of a collaborative effort where half is my own work and Professor Feryal Erhun and Professor Tim Kraft contributed to the writing of the paper and formulation of the framework. The large majority of Chapter 3 is my own contribution (idea, literature, and analysis), and the paper was written in collaboration with Professor Dominique Lauga and Professor L. Beril Toktay. Finally, Chapter 4 was written in collaboration with Professor Paul Kattuman and the large majority is my own work (literature, methodology, analysis).

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Abstract

In 2030, we will reach the deadline of most Sustainable Development Goals (SDGs) set by the United Nations, which represent a universal call to end poverty and protect the planet. The SDGs are distinct from previous environmental and social targets because they recognise that development must balance economic, social and environmental sustainability since interventions in one area may affect outcomes in the others. The goals are therefore an integrated and balanced package and, following that same logic, will require an interdisciplinary and multi-stakeholder approach. This thesis integrates the fields of environmental economics and sustainable operations to uncover novel research questions and to provide more holistic solutions that will advance the attainment of the SDGs. This work focuses in particular on social and environmental issues in supply chain contexts that key organisations have identified as some of the most pressing challenges.

The first chapter looks at the triple-A (agile, adaptive, aligned) supply chain framework through the lens of sustainability. The concept of triple-A supply chains is that the best supply chains are not only fast and cost-effective but also agile, adaptable, and aligned. This notion has been studied extensively and has influenced the management approach in leading companies around the world. Yet since the triple-A concept was first developed, supply chains have become increasingly global, connected, and interdependent. The increased complexity of global supply chains has reduced much-needed visibility, further complicating their management, while the growing connectivity and interdependence among different stakeholders have led to many unforeseen environmental and social issues. In light of these new challenges and demands, we revisit the original triple-A definitions and expand these concepts for a more socially and environmentally conscientious world. This new framework can help firms see sustainability as a new opportunity rather than an additional constraint. We also discuss potential enablers of and barriers to sustainable triple-A supply chains and give an overview of sustainability topics yet to be explored in the supply chain literature.

The second chapter takes a unique look at the effect of waste regulations on the economic and environmental performance of the reverse supply chain. The project was motivated by my collaboration with Europol, the European Law Enforcement Agency. Every year, the world produces over $62.5 billion worth of electronic and electrical waste (e-waste), but only 10% of that is recycled in compliance with regulations. To minimise the negative impact of unwanted waste disposal methods such as dumping and export, policymakers have implemented or increased the enforcement of laws designed to combat them. Even so, violations are rampant as proprietary information and a high degree of heterogeneity between firms render monitoring imperfect. Decentralised waste disposal chains, a common form of inter-business organisation, compound this problem as firms also have limited information available on the other chain partner, therefore creating complex interactions between firm behaviour and policy interventions. Against this background, we analyse the effects of policy options on firm profits and compliance. Our analysis reveals that primarily focusing on penalizing dumping by treatment operators can worsen waste chain outcomes. Solely focusing on penalizing low-quality waste exports, a common intervention in practice, can also backfire. Instead, penalizing manufacturers for downstream dumping should be given consideration. In addition, the asymmetry in export burden between waste quality levels should be reduced, which improves both waste outcomes and treatment operator profits.

My third and final chapter focuses on alleviating poverty of rural smallholders. The project was built on findings from a research visit to the UN Environment Programme (UNEP) in Nairobi, the global environmental authority within the United Nations system, and from a continuous collaboration with the UNEP-WCMC, the conservation unit of the UN. Over 70% of the poor live in rural areas in developing countries and smallholder farmers are among the poorest. Since hundreds of multinational buyers have made commitments to source responsibly and poverty eradication is a fundamental objective of the SDGs, the importance of addressing rural poverty in a sustainable manner is self-evident. Traditionally, rural smallholders were primarily viewed as farmers, but development projects have shown that smallholders typically pursue a diverse portfolio of activities to complement their farming income. We therefore explore the link between rural poverty and livelihood composition, a factor rarely captured in current poverty analyses. Using a sample of over 4,000 rural smallholders across 16 developing countries, we explore the poverty impact of compositional aspects of household income, explicitly differentiating between income derived from environmental, farm, and non-farm sources. Our findings have important implications for how we understand rural livelihoods and how policymakers and buyers of commodities can improve the ability of smallholders to develop value-creating portfolios.

With under ten years left to achieve the Sustainable Development Goals, we have entered a decade where ambitious action is crucial. My research advances the attainment of these goals by applying frameworks in operations management, such as sustainable supply chain management, to challenges identified in Environmental Economics, such as illicit waste management and poverty. I hope that this thesis and the work built on it will help accelerate progress on the SDGs by showing the benefits of an integrated approach.

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Chapter 1

Introduction

The 17 United Nations Sustainable Development Goals (SDGs) were adopted in 2015 by the United Nations General Assembly to restore the planet and protect the most vulnerable communities. The goals balance the three dimensions of sustainable development: economic, social and environmental. Yet, challenges remain. Environmental degradation, pollution, and overexploitation of natural resources continue to be immediate threats to the natural world and inclusive development efforts. Each year, millions of hectares of forest are destroyed, primarily driven by agricultural expansion, while natural resources are used unsustainably. Rather than being formally treated and recycled, waste is still mostly informally handled in developing countries through open burning or acid baths, both of which pollute the environment and result in the loss of valuable and scarce resources. On top of that, the COVID-19 crisis has caused the first increase in poverty in decades (United Nations, 2020).

Most of the SDGs focus on specific issues or themes which are associated with specific stakeholders and scientific communities. The goals cite, for instance, the specific need for clean energy technology, food security and improved nutrition, quality education, resilient infrastructure, combating climate change etc. However, the economic, social, and environmental issues underlying the goals are closely interlinked and thus indivisible. As such, we require integrated approaches to identify "win-win" cases and avoid the accomplishment of one goal undermining the progress of another.

One exceptionally promising area for "win-win" solutions is supply chain sustainability: a cross-cutting topic that applies to several issue areas. The need for sustainable production patterns (Goal 12) explicitly highlights the role of supply chains for a sustainable global economy. The impact of global supply chains can, however, reach far beyond this. For instance, responsible sourcing practices can help alleviate poverty

(Goal 1) and protect natural resources (Goal 15), while responsible waste management practices can reduce pollution and improve health and well-being (Goal 3) as well as decrease the need for the extraction of raw materials (Goal 15). In contrast, supply chains in which sustainability commitments are not emphasized may significantly increase the exports of developing countries (Goal 17) but at the same time exacerbate deforestation and bad labour practices. These often complex interlinkages between the goals further accentuate the importance of an interdisciplinary approach by involving disciplines beyond the traditional operations management research cluster.

The goal of this dissertation is to help solve pressing sustainability issues, both social and environmental, in supply chain contexts, and integrated perspectives lie at the core. Specifically, many of the identified supply chain solutions require a consolidated approach between operations management frameworks and development and environmental economics research. In doing this, I uncover gaps in the literature from which interesting and novel research questions emerge. The applicability and impact of the research outcomes, and their potential to provide solutions for the Sustainable Development Goals, were also major considerations for the formulation of the research questions. I therefore developed my research in collaboration with key industry partners to provide holistic and relevant solutions that will advance the attainment of the SDGs.

1.1 Role of supply chains

Companies can contribute significantly to the SDGs through their supply chain practices, and an increasing number of businesses realise the necessity as well as the benefits of incorporating sustainability requirements into their supply chains. For example, sustainability appeals to a growing market segment and can help firms explore entirely new markets, design innovative products, and manage legal and reputational risks.

Clearly, the business case for supply chain sustainability has evolved, but so have the challenges. Supply chains have become increasingly global, connected, and interdependent. As a result, many companies cite the difficulty of mapping their supply chain partners even below the first tier and rarely have direct contractual relationships with them (Villena and Gioia, 2018). The increased complexity of global supply chains has reduced much-needed visibility, further complicating their management, while the growing connectivity and interdependence among different stakeholders have led to many unforeseen environmental and social issues. Unexpected consequences are problematic as good practices or innovation in one area cannot make up for doing harm in another.

Traditionally, the best supply chains were seen as not only fast and cost-effective, but also agile, adaptable, and aligned, i.e., triple-A (Lee et al., 2004). Agile supply chains respond quickly to short-term and sudden changes in market demand or supply and handle external disruptions smoothly; adaptable supply chains adjust their supply networks to meet structural shifts in the market; and aligned supply chains create incentives for supply chain partners to improve outcomes. Triple-A supply chains are characterised by achieving all these feats.

In today's environment, new demands outside of traditional market forces are compelling companies to revisit these concepts. For example, agile fast fashion supply chains can serve customers based on the latest trends thanks to the short lead times, but are exceptionally wasteful and polluting in doing so. The definitions of the three As must therefore be expanded in the context of sustainable supply chains to reveal the additional capabilities needed for social and environmental sustainability. The second chapter, by **?**, explores how supply chains should evolve to meet the increasing need and demand for sustainability and concludes with potential enablers of and barriers to sustainable triple-A supply chains.

1.2 Priority issues in sustainability

Supply chains are one of the most important levers for businesses to make a positive impact on society and the environment. As governments are adopting the SDGs, we now know there are compelling reasons and enormous opportunities for supply chains to evolve alongside of these goals. At the same time, government policy is an important facilitator of this move, but it must avoid disturbing areas where markets are already functioning well, which could end up undermining the goals. This is a challenging field to navigate.

The next two chapters develop two high-priority issues where the pursuit of sustainable supply chains can be a powerful tool to advance the Sustainable Development Goals, both of which were identified in collaboration with key intergovernmental organisations: responsible waste management, which considers downstream risks, and poverty alleviation for rural smallholders, which considers upstream opportunities. These areas are as crucial for firms as they are for governments and agencies that work to attain the SDGs. Coordinated action can therefore extend the impact of supply chain sustainability.

The third chapter, on waste management, was inspired by a collaboration with Europol, the European law enforcement agency. During a visit to their headquarters in 2015, we discussed at length several key issues the environmental crime unit was facing, particularly in relation to the trade in hazardous and electronic waste (e-waste). For instance, several estimates suggest that only 20% of e-waste is formally recycled, which will only become more problematic as it is the fastest growing waste stream (United Nations, 2020). There are strict rules in the European Union to make sure the precious metals in e-waste are extracted without the toxic substances harming public health or the environment. While these regulations are necessary, they impose large costs on firms, and it can become more lucrative to export waste to developing countries where standards are lower, even though this is a criminal offense (Europol, 2017).

Based on the information provided by Europol, I identified commonalities across cases and uncovered overarching trends to develop a game theoretic model that captures the firm incentives and key waste flows. A modelling framework designed in close collaboration with experts is an effective approach for the analysis of illicit markets considering the lack of data due to the hidden nature of these activities. I discovered that proprietary information is a key inhibitor of effective monitoring in the waste market and two main types of proprietary information were present: the lack of accurate information on the quality of the waste stream and the lack of accurate information on the efficiency of treatment facilities. Even certifications have proven insufficient: certified, prominent companies are frequently found to engage in non-compliant behaviour (Rucevska et al., 2015). Decentralized waste disposal chains, a common form of inter-business organization, compound the information problem as firms also have limited information available on the other chain partner, creating complex interactions between firm behaviour and policy interventions.

I explore how we can design waste regulations that avoid violations and that create incentives for all firms in the chain to pursue proper treatment and recycling of wastes. The cooperation of all firms is a crucial step, as a single firm deviating from compliance is enough to cause waste to leak out of the formal system. The research outcomes provide insights for firms and policymakers that need to operate in markets with high levels of information asymmetry. Certain intuitive policies that are currently used were revealed to increase violations or negatively affect profits of compliant firms, while other less obvious alternatives led to better results. The key insights of this study can be found in the conclusion.

The fourth chapter, on rural poverty alleviation, was inspired by a collaboration with the United Nations Environment Programme (UNEP). In a continuous collaborative effort with UNEP-WCMC, the conservation unit of the UNEP, I explored the strong link between poverty and forest management and how rural communities can be transformed to be both the target beneficiaries of and contributors to natural resources. During a research visit to the UNEP in Nairobi I continued this line of research, but with a focus on livelihood portfolios. Specifically, in the Kavango-Zambezi area in Southern Africa, frequent human-wildlife conflicts and growing land-use challenges due to farming activities are rapidly degrading natural resources and are driving the decline in populations of protected species. The UNEP wanted to explore whether (combinations of) novel livelihood strategies can create enabling incentives for the local communities to protect wildlife and their natural habitats. In other words, what livelihood combinations help communities manage their portfolios in a more sustainable way, while ensuring that they are also beneficiaries of any changes?

The application of livelihood portfolios was specific to that region, but smallholders all over the world are active in multiple economic activities, and the natural environment is often an important contributor to their income. Estimates suggest that rural smallholder households living near forested areas derive 22% of their income from these forest sources (World Bank Group, 2016). This income is often referred to as 'the hidden harvest' and is rarely considered in livelihood studies. Degradation of these forests is of primary concern to the environmental SDG objectives, but may also impact poverty (World Bank, 2018).

Rural smallholders provide crucial commodities for global supply chains, and an increasing number of companies and social enterprises are starting to source directly from the poor in an effort to reduce poverty (Sodhi and Tang, 2011, 2014). Such interventions have created possibilities for individual households to improve their income from a specific source, such as business or farming (Tang, 2018). Two key issues are still overlooked: First, livelihood composition matters, rather than just the level of income. Second, since poverty is a community construct, growing individual incomes can have ambiguous effects on poverty depending on where in the income distribution that growth occurs. These points should be an important consideration in designing socially responsible procurement strategies. We need a system-wide perspective of the portfolio dimension of poverty on a community level to be able to address these points. I therefore explore how livelihood portfolios of rural smallholders have a bearing on village-level poverty.

1.3 Integration of fields

Sustainability is a cross-disciplinary topic and as such we should maintain a broad scope. In the identified sustainability issues, there exists an obvious link between operations management and economics. Studies that integrate these fields are relevant for a wider audience and can tackle broader questions.

The literature on waste management is spread out over two main fields: environmental economics and reverse supply chain management. The environmental and social implications of violations in waste management have featured in a long-standing stream of literature in environmental economics. These studies have focused on the effects of different policy measures on potential non-compliance, but are silent on the fact that in waste management, a chain of firms and agents are involved that each have an incentive to violate regulations. If a single agent in the waste chain decides against proper management of the waste, this is enough to cause waste to leak from the formal treatment process, severely harming public health and the environment. This is the angle that operations management can explore.

The reverse supply chain literature in operations management has studied in great detail the interactions between the agents, from consumers through original equipment manufacturers to recyclers and treatment operators. However, the possibility of illegal activities, which is rampant in practice, was excluded from those analyses. I concluded that to understand this problem, the advantage would lie in a cross-disciplinary approach by taking the important characteristics from both sides: the possibility for firms to non-comply in response to environmental and social regulations, and the supply chain view to reveal the consequences of firm interactions on violations and compliance.

Livelihoods of rural smallholders, which feature in the third chapter, have been extensively studied in the environmental and development economics literature. One major finding of these studies was the importance of natural resources as a complement to farm and off-farm income (Angelsen et al., 2014). This is especially relevant since environmental income is typically overlooked in country-level poverty studies, which also do not discriminate between sources of income (e.g. Bluhm et al. (2018)). A portfolio perspective of poverty at the disaggregated level is therefore missing.

Rural poverty alleviation is rapidly gaining attention in operations management as one of the necessary conditions for responsible sourcing, but it is still a nascent area. There is an enormous opportunity for operations management to deliver solutions for the missing elements that exist on a disaggregated level. Most of the work on rural poverty to date has studied how specific operational levers can grow a single income component of an individual (e.g. specific contracts or sales channels that improve income from farming or self-owned business) (e.g. De Zegher et al. (2019); Tang (2018)). I believe that operational interventions can be particularly promising if these can shape the different income components of livelihood portfolios simultaneously, rather than focusing on the optimisation of a single sub-component like farming.

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Chapter 2

Sustainable Triple-A Supply Chains

In his 2004 article, Professor Hau Lee argues that the best supply chains are not only fast and cost-effective but also *agile*, *adaptable*, and *aligned*. The concept of triple-A supply chains has been extensively studied in academic and trade publications and integrated into numerous operations and supply chain management curricula. It has also influenced the management approach of leaders around the world. Yet, since the triple-A concept was first developed, supply chains have become increasingly global, connected, and interdependent. The increased complexity of global supply chains has reduced much-needed visibility, further complicating their management, while the growing connectivity and interdependence among different stakeholders have led to many unforeseen environmental and social issues. As a result, Professor Lee's emphasis on triple-A supply chains is even more relevant today. In light of these new challenges and demands, we revisit the original triple-A definitions of agile, adaptable, and aligned, expanding these concepts for a more socially and environmentally conscientious world. We also discuss potential enablers of and barriers to sustainable triple-A supply chains.

2.1 Introduction

In his 2004 article, Professor Hau Lee argues that the best supply chains are not only fast and cost-effective, but they are also agile, adaptable, and aligned (Lee et al., 2004). That is, triple-A supply chains (i) respond quickly to short-term and sudden changes in market demand or supply and handle external disruptions smoothly (*agile*), (ii) adjust their supply networks to meet structural shifts in the market (*adaptable*), and (iii) create incentives for all supply chain partners to achieve better outcomes (*aligned*). Based on this definition, an agile supply chain combines shared, centralised intelligence on demand and supply data with efficient, decentralised execution. An adaptive supply chain requires flexible network relationships alongside a change management focus. Adaptability also involves routine collection of intelligence on market product needs and continual technological evolution. Finally, alignment necessitates clearly defined roles and responsibilities and extended, joint performance measures that adjust risk, costs, and rewards across the supply chain.

Since the publication of Professor Lee's article, its concepts and examples (such as Zara's agile supply chain and HP's adaptation of inkjet printer production over the product's life cycle) have appeared in academic and trade publications and have made their way into operations and supply chain management curricula. The article has been cited over 2,000 times and has influenced the management approach of leaders worldwide.

Yet in the past 16 years, supply chains have become increasingly global, connected, and interdependent. The greater complexity of global supply chains has reduced much-needed visibility, further complicating their management. The growing connectivity and interdependence among different stakeholders within supply chains have led to many unforeseen environmental and social issues. Consider the following.

2.1.1 Agility

From their outset, Zara and H&M have been recognised for their agility, which is enabled by their underlying fast-fashion models. Historically, fast fashion went against the grain of the fashion industry's long lead time assortment model by focusing instead on meeting customer demand through the rapid design, production, and stocking of new fashions. Today, however, the environmental implications of fast-fashion models have brought them under scrutiny.

Consumers are increasingly demanding more sustainable clothing options (Masunaga, 2019), and activists and governments are pressuring fast-fashion companies to reduce their carbon footprint, eliminate waste, and improve sourcing standards (Howard, 2019; Lee, 2019).

In principle, the short lead times and small production quantities associated with fast-fashion models should reduce waste, a common issue in the apparel industry. However, this does not occur in practice. Fast-fashion models are based on continual assortment turnover and promotion of consumption, which amplify the existing waste issues in the fashion industry. One such issue is water: the industry produces nearly 20% of global wastewater, and this share is only expected to rise as the production of discardable clothing increases. A second issue is textile waste, which is mostly generated after the use phase: less than 1% of clothes are recycled, and the average consumer throws away approximately 70 pounds of clothing every year. Overall, the apparel industry contributes to global emissions more than aviation and shipping combined (Ellen MacArthur Foundation, 2017).

2.1.2 Adaptability

In addition to reacting to unexpected changes in supply and demand, companies must also be able to adapt their supply chains to more long-term market shifts. Outsourcing can help supply chains become more adaptable by securing economies of scale, providing the flexibility to change sourcing locations and relocate production more easily (Lee et al., 2004). To use the classic example, the success of HP's inkjet printer was partly due to outsourcing, which allowed HP to reduce manufacturing costs once the technology had matured. Similarly, Microsoft's successful launch of the Xbox and its ability to compete with market leader Sony on both cost and speed were, in part, due to outsourcing: Microsoft outsourced Xbox's production to Flextronics, which had production facilities close to Microsoft's target markets and in lower-cost countries in Asia.

As supply chains have grown in complexity, however, globalisation, and outsourcing now often lead companies to lose control of their sourcing. Consider, for example, multinationals that source palm oil, a notoriously complex supply chain. Many of these companies have been at the center of controversy after several investigations revealed human rights violations and illegal deforestation activities occurring at palm oil plantations (Amnesty International, 2016; Greenpeace, 2018). An intermediary, Wilmar, controls 45% of the global palm oil trade; thus, a single firm (even a large multinational) has very little power to change industry standards. The inability to transform relationships and control suppliers significantly reduces a firm's ability to adapt its supply chain and make it more sustainable.

2.1.3 Alignment

Lastly, companies must align incentives and share information such that all supply chain partners pursue the same interests and maximise the chain's performance. For example, Seven-Eleven Japan was famous for its emphasis on alignment, as even before the advent of the internet, it used satellite connections and real-time data on customer preferences to align suppliers, logistics, and retailers. This alignment created time and cost savings for the whole supply chain. Unfortunately, examples like this remain rare, as the greater complexity of supply chains has proven a significant challenge to their alignment. *Even if* firms know who their upper-tier suppliers are, they rarely have contractual relationships with them (Villena and Gioia, 2018). New environmental and social responsibility pressures further complicate the equitable division of cost and risk within a supply chain, especially since these externalities are rarely, if ever, included in cost and risk considerations.

In this context, alignment has become even more crucial. The immediacy of this need is underscored by a recent report released by The Sustainability Consortium, which urges companies to prepare their supply chains for further potential weather-related disruption risks due to climate change (Holbrook, 2020). Still, many companies fail to act on opportunities to align the environmental strategies of their supply chains. For example, a 2017 report by the Carbon Disclosure Project found that while major brands have made progress in reducing their own emissions (i.e., Scope 1 and 2 emissions), only 23% of the brands surveyed worked with their suppliers to reduce the suppliers' emissions (i.e., Scope 3 emissions). Reducing suppliers' emissions is critical to addressing climate change, as the carbon emissions of upstream supply chains are four times greater than those of companies' direct operations (Mead, 2018). To improve their positions on environmental issues like carbon emissions and to create sustainable supply chains, companies must align the environmental decision making of entities in their supply chains just as they have done to improve pricing and quality.

In light of the examples and discussions above, Professor Lee's emphasis on triple-A supply chains is even more relevant today. However, the characterisation and operationalisation of agility, adaptability, and alignment within today's global supply chains is a more involved undertaking. Thus, we revisit the triple- A supply chain definitions to investigate how these concepts can be expanded in response to the increasing need and demand for sustainability. We also discuss potential enablers of and barriers to sustainable triple-A supply chains. Throughout, we highlight examples from practice to identify interesting trends that may merit further study by the operations management community. We do not provide an extensive review of the existing sustainable operations management literature; we refer readers seeking such a review to Lee and Tang (2018) and Atasu et al. (2020).

2.2 Building Sustainable Triple-A Supply Chains

Due in part to the increase in sustainability-related pressures companies face today, the potential meanings of agile, adaptable, and aligned in the supply chain context have evolved since 2004. This evolution creates an opportunity to reframe the definition of each term in the context of a sustainable triple-A supply chain. Our goal in this section is to revisit the definitions of agile, adaptable, and aligned supply chains to highlight, through examples, the additional capabilities needed for social and environmental sustainability (Table 2.1).

Table 2.1 Revisiting the Definitions to Incorporate Sustainability

	The Triple-A Supply Chain Lee et al. (2004)	**Sustainable Triple-A Supply Chains** Erhun, Kraft and Wijnsma (2020)
Agile	Respond to short-term changes in consumer demand or supply quickly; handle external disruptions smoothly	Respond to a broader set of stakeholder demands that includes regulators, activists, and employees
Adaptable	Adjust supply networks to meet structural shifts in the market; quickly spot trends in the marketplace	Develop innovative ways to better control the supply chain; create market trends
Aligned	Create incentives for all supply chain partners to achieve better performance, both as a whole and individually	Extend alignment to points further up (upper tiers) and down (reverse) the supply chain; broaden the view of alignment to incorporate the consumer perspective

2.2.1 Agility

Agility describes a company's ability to respond to short-term changes in market demand or supply quickly and handle external disruptions smoothly. This definition emphasises the need for companies to be *reactive* and make difficult *short-term* decisions. However, in today's environment, new demands outside of traditional market forces are compelling companies to revisit this view of agility. In particular, sustainable agile supply chains can no longer solely focus on short-term changes in the market and maximising shareholder value.[1] Instead, the emphasis must be on reacting to a broader

[1]The pressure to act on sustainability can, of course, be stock-price driven. In 2018, ESG (Environmental, Social, and Corporate Governance) investing grew to over $30 trillion (Stevens, 2020). This increasing trend of ESG-driven investment represents a considerable risk for any public company not focused on improving its sustainability performance, as incidents can lead to significant stock value losses. For example, online retailer Boohoo recently saw its shares drop by 12% after reports surfaced about employees at one of its suppliers receiving wages less than half of minimum wage (Mulier and Hipwell, 2020). In the United States, it is estimated that these types of ESG incidents have erased almost half a trillion dollars' worth of value from public companies over the past 5 years

set of *stakeholder* demands. Companies "must also invest in their employees, protect the environment and deal fairly and ethically with their suppliers" (Gelles and Yaffe-Bellany, 2019) and address calls from external stakeholders such as non-governmental organisations (NGOs), activists, and regulators (Gartenberg and Serafeim, 2019).

Such stakeholder demand had consequences for Patagonia in 2015, when it was attacked by a PETA video demonstrating animal cruelty at Patagonia's wool supplier. This animal mistreatment occurred despite the fact that Patagonia, which is forward thinking on sustainability issues, had worked closely with the supplier to establish the wool operations. Consequently, Patagonia immediately stopped sourcing wool, a break that lasted 3 years, to correct its wool supply chain issues (Kapadia, 2018). Furthermore, it worked with apparel industry leaders to develop a new Responsible Wool Standard. In this example, an external activist, rather than consumers or a natural disaster, created the shock to Patagonia's supply (and, in turn, demand), requiring a swift response from Patagonia to avoid escalation.

In addition to advocating for sustainable sourcing in the apparel industry, environmentalists and activists are also pushing brands to improve the industry's environmental impact by lowering their production and sales volume. Agility typically meant that supply had to match changes in demand as quickly as possible and responding to these activist demands would not necessarily align with those from consumers. Nonetheless, from one year to the next, Gucci reduced its offerings in 2021 to just two seasons in support of a less wasteful fashion system. It is the first major brand to undertake this move and a clear overhaul of the customer-centric system from which the company has profited in the past (Cartner-Morley, 2020). In contrast, Zara's approach to fashion remains exclusively customer-centric offering no less than 52 seasons. The company argues that it is ultimately in shoppers' hands to decide whether and how to purchase (Holgate, 2019; Patel, 2019). While this viewpoint puts less pressure on Zara to reinvent itself in the short term, the rapidly growing sentiment against fast fashion on multiple fronts (e.g. waste, chemical usage, and carbon footprints) will likely test Zara's agility sooner rather than later.

Activism is not the only source of sustainability related external disruption. Regulations on social and environmental responsibility can also test a company's supply chain agility by posing unique challenges. These challenges are due to constant shifts in extraordinary complex regulatory requirements requiring firms to constantly respond

(Flood, 2019). This level of impact is also why socially responsible investing is considered the next wave of shareholder activism (Driebusch, 2020).

to those shifts. One example is carbon legislation. Since 2013, the UK's emissions regulations have required public companies to report their carbon emissions (Sweet, 2013). Requirements were intensified in 2019, obligating both public and large private firms to report their energy use (HM Government, 2019). In addition to following these UK regulations (which are so complicated that a previous scheme was discontinued due to its complexity (Chestney, 2018)), firms must also monitor and potentially address EU regulations following Brexit. Thus, constantly shifting regulations require companies to continuously respond with their operational processes, data collection, and day-to-day reporting to ensure that their supply chains remain in compliance. Another example that will test firms' regulatory agility is the implementation of the Non-financial Reporting Directive (NFRD). Under this directive, companies are required to disclose information and publish reports on their social responsibility policies (respect for human rights; anti-corruption and bribery; diversity; risks and risk management). This means that the firm must immediately respond when it underperforms on certain indicators, not only to ensure compliance but also to keep a competitive position in the market as the information is now freely available.

An agile approach to reacting to regulations, implementing the necessary changes, and responding to the outcomes means that teams must prioritise investments and operational changes by taking an incremental approach to addressing requirements (Gittfried et al., 2017). This incremental approach avoids abrupt implementations of costly and often inflexible methods for meeting regulatory requirements. Moreover, it can help achieve cost savings through e.g. increased awareness of energy use, despite potentially high initial costs and operational complexity. It can even facilitate proactive compliance as small investments are easier to implement and justify without immediate regulatory need. One firm that utilised such an incremental strategy is Unilever, which was also one of the few firms that complied with the UK carbon regulations earlier than required. Over time, Unilever implemented many of its own Sustainable Living Plan goals and could easily tweak them to meet carbon disclosure requirements before they were mandatory (Unilever, 2019). Therefore, having agile operational, data collection, and reporting systems that can be adjusted to meet new regulatory requirements in the short-run can help firms build an adaptable supply chain in the long-run. The ability to spot and plan for these regulatory demands ahead of time is discussed in the next section.

Stakeholder pressures are not solely the purview of external stakeholders such as activists and regulators. Internal stakeholders can also place unforeseen demands on firms and cause internal disruption. Consider the recent issues and bad publicity Amazon incurred when word leaked that the company pressured employees not to speak out against climate change. This incident is part of a bigger trend of Amazon employees urging the company to address its environmental impact (Palmer, 2020). When companies like Amazon do not manage the internal demands of an increasingly socially conscious workforce, they may face potential operational disruption caused by these dissatisfied employees.

In addition to new stakeholder demands, the growing role of reverse supply chains also affects agility. A company's *reverse supply chain* is concerned with retrieving, reusing, and recycling end-of-life products. In this context, social and environmental responsibility violations, such as the illegal export or dumping of waste, frequently occur, exposing brands to compliance and reputation risk while devastating the environment and public health (Wijnsma et al., 2021). For instance, the nonprofit organisation Tearfund recently found that four multinational drink companies are responsible for approximately half a million tons of plastic pollution every day in just six developing countries. The nonprofit urged these companies to eliminate plastic packaging waste that currently ends up dumped or burnt due to a lack of recycling infrastructure (Laville, 2020). Regulatory demands on the reverse supply chain have also become stricter. Among such requirements, Extended Producer Responsibility regulations place the responsibility for the post-consumer phase of certain goods on producers, which requires an agile reverse logistics system to manage the return and recycling of a large volume and variety of products in varying stages of use (Atasu et al., 2009). For instance, the collection of used electronics will result in a stock of working, repairable, and non-repairable products, of which some will contain hazardous components mixed with precious, recoverable metals. An agile system is crucial as the collection points and composition of this stock will vary from day to day.

When handled properly, agile management of the reverse supply chain can create competitive and cost advantages. For instance, through product use-phase data, HP's Instant Ink service detects when a printer's cartridge needs to be replaced, allowing the firm to predict and immediately react to demand. It automatically ships a replacement, facilitates the empty cartridge's return, and reprocesses it in its advanced facilities. This process reduces the carbon footprint of the ink purchase and return by 84% and reduces material consumption by 57% (Leurent and Cronin, 2019).

To create an agile and sustainable supply chain, companies must broaden their customer-centric approach to incorporate an expanded set of diverse stakeholders that includes activists, regulators, and employees. In doing so, they must ensure the entire value chain, including the reverse supply chain, can meet these new, continuously changing, and possibly opposing, demands. If they do not, then the additional constraints and requirements arising from issues such as CO2 emissions, waste generation, and labour practices will make companies even less agile in the current landscape.

2.2.2 Adaptability

Adaptability refers to a company's ability to spot trends in the marketplace and adjust its supply network to meet these structural shifts. This definition emphasises the need for companies to be *proactive* and have a more *long-term*, strategic view. However, creating adaptable *and* sustainable supply chains requires companies to do more than simply monitor trends and adjust their supply networks as needed. They must further enhance their influence by exploring innovative ways to control their supply chains better.

One way to adapt a supply network is to develop innovative new sources of supply. Consider Dell, which established the first commercial-scale global supply chain for ocean-bound plastics. The firm tackled a significant environmental problem by leveraging its strength in supply chain management and its knowledge of closed-loop recycling of materials from its products. By collecting and upcycling unwanted and harmful plastics, Dell created an environmental benefit and established a less expensive supply comparable in quality to traditional sources of plastic (Anupindi and Hoffman, 2018).

Adapting a supply network to become more sustainable may not always require an extensive degree of innovation. Instead, firms are finding value through sustainability by restructuring existing supply networks. Consider Haiti Hope, a public-private partnership between Coca-Cola, Technoserve (an NGO), the Inter-American Development Bank Group, and the United States Agency for International Development (Edmondson and Harvey, 2016). The Haiti Hope project was a social development project designed to help Haitian farmers grow mangos more efficiently and secure access to international markets. The project's underlying economic goal was to raise the farmers' standard of living and, ultimately, contribute to the Haitian economy's revitalisation after the 2010 earthquake. The partnership invested funds and resources to educate farmers on best practices and improve the local logistics infrastructure. Furthermore, it established a robust intermediary presence between buyers and farmers, which not only strengthened small shareholder farmers' leverage in the market but also improved the quality and consistency of the product produced. The project benefited not only the farmers and their communities but also Coca-Cola; by developing the supply chain for mangos in Haiti, Coca-Cola reduced its costs and lead times by locally sourcing its fruit juices.

Companies can also adapt their supply chains to be more sustainable through vertical integration, which allows greater control. Consider, for example, the guitar industry, which sources a considerable amount of ebony wood, a key material in guitar production. In the early 2010s, high demand and low supply of ebony led to widespread illegal logging, which exposed many guitar manufacturers, such as Gibson Guitar[2], to compliance and reputation risks. Gibson's competitor, Taylor Guitars, sourced its ebony wood historically from the Crelicam mill in Cameroon, which, in turn, sourced its raw wood from several small suppliers in the region. In 2011, the owner of Taylor Guitars, Bob Taylor, traveled to Cameroon to better understand the sourcing process for the ebony wood that had made Gibson the center of controversy. On his trip, Taylor discovered some disturbing facts about the ebony sourcing process. For example, due to the strong industry preference for pure black ebony wood (rather than ebony wood with streaks of colour), wood suppliers, on average, cut down ten trees to find one tree with the desired pure black colour. Taylor also noticed many ethical issues in the mill's labour practices.

To mitigate the risks associated with responsibility violations and fix the issues at the mill and with the wood suppliers, Taylor Guitars vertically integrated by purchasing the Crelicam mill. In doing so, Taylor Guitars established labour practice standards at the mill comparable to those found in the United States. The mill began to accept wood with stripes from the wood suppliers at prices equal to those for pure black wood (Taylor Guitars, 2020b). Purchasing the Crelicam mill also made Taylor Guitars a supplier to its competitors. Using its position as both a supplier and a producer, the company helped re-educate the market (both consumers and competitors) on striped ebony wood. For instance, the firm launched several campaigns to encourage the adoption of marbled ebony wood and started using it for its highest-end guitars. In this regard, Taylor Guitars did not spot a trend but rather created a trend of striped-ebony guitars (Orsdemir et al., 2019; Taylor Guitars, 2020a).

As these examples demonstrate, firms interested in creating an adaptable and sustainable supply chain must look beyond simply adjusting their supply chains and find

[2] In 2009 and 2011, Gibson Guitar was raided for using illegally sourced wood. These raids revealed that the firm had failed to successfully adapt to new sourcing regulations that made US companies responsible for ensuring that their trading partners throughout the timber supply chain obey all laws in all countries.

innovative ways to take more control of their supply networks. This new approach may require disruptive innovation that emphasises sustainability in products/services, processes, and infrastructure. In so doing, a firm can transcend traditional relationships and establish more cooperative supply networks with fluid roles. These innovations can not only help to educate suppliers and customers but may also create new market opportunities.

2.2.3 Alignment

When entities within a supply chain are not aligned, siloed decision making can lead to poor overall performance and inefficient outcomes. When a firm aligns its supply chain properly, however, it creates incentives for all supply chain partners to achieve better performance, both collectively and individually. Whereas agility and adaptability focus on the firm itself, this definition emphasises the need for companies to look at all their supply chain partners. Based on the traditional concept of alignment, such efforts generally focus on the interactions between a firm and its direct suppliers in the forward supply chain. However, the most detrimental sustainability issues usually occur (i) in the upper tiers of supply chains and (ii) downstream in the reverse supply chain after products reach end-of-life or are discarded.[3]. Therefore, the demand for more sustainable supply chains creates additional pressures for companies to extend the idea of alignment further in both upstream and downstream directions. Also, companies are under new pressure to demonstrate that products are being made and sourced ethically. This pressure is forcing them to broaden their view of supply chain alignment to consider the impact and demands of consumers in addition to the alignment between brands, manufacturers, and suppliers.

This shift has significant implications for how companies monitor their supply chains. Specifically, an essential characteristic of an aligned supply chain is that information is shared freely between entities, including suppliers and customers (Lee et al., 2004). As the complexity and scope of supply chains have increased, more and more companies

[3] A study of 3,922 supplier relationships found that Tier 2 suppliers committed, on average, 18% more violations per audit than Tier 1 suppliers; Tier 3 committed 27% more (Sedex, 2013) Incidents like the Rana Plaza collapse in Bangladesh in 2013, in which over 1,100 workers died when a garment factory collapsed, not only confirm the findings from the Sedex study but also highlight companies' lack of visibility into these upper tiers of their supply chains (Yardley, 2013). In terms of the reverse supply chain, images of landfills full of discarded garments from known apparel brands frequently cause public outcry (Wicker, 2016). Electronic companies face similar objections when branded products are dumped or manually dismantled under dire working conditions in developing countries (Gnanasagaran, 2018).

realise the need to gain visibility into and collaborate with the practices of their supply chain partners (Kraft et al., 2018). Yet, establishing visibility into a supply chain (let alone improving suppliers' and customers' practices) remains a challenge and requires an extensive commitment of time and resources (Doorey, 2011). Companies are making efforts, but examples of success in this regard are few and far between.

In the apparel industry, globalisation has led many companies to search for inexpensive labour sources in developing countries. This expansion has challenged firms' abilities to maintain alignment and gain visibility within their supply chains.[4] More socially conscious apparel brands are now forced to exert further effort to maintain alignment. For example, Patagonia annually audits not only 100% of its Tier 1 suppliers but also a subset of Tier 2 suppliers that constitute 80% of its total material cost (Patagonia, 2017). It has even begun mapping its supply chains to the farm level to ensure farms meet its standards (Patagonia, 2020). Following a recommended method for promoting and achieving alignment (Lee et al., 2004), the firm freely discloses its information to customers and vendors (Bateman and Bonanni, 2019). An important aspect of Patagonia's focus on alignment is that it includes downstream stakeholders. For example, in 2019, its fleece vests practically became the new corporate uniform for bankers on Wall Street: an apparent misalignment between customer and company for a firm that prides itself on being a sustainable outdoor brand. To realign its customer base with its corporate strategy, the firm shifted the focus of its corporate sales program to organisations that meet specific environmental, social, and transparency standards (B-Corp), a move that excluded many financial and tech firms.

Another example is Goodio, a Finnish craft chocolate maker that is committed to putting purpose over profit and recognises the importance of transparency[5] in achieving this goal (Hämäläinen et al., 2020). Goodio bases its business model on "radical transparency," i.e., creating end-to-end transparency in its supply chain so that consumers know they are purchasing from a brand they can trust. By leveraging its strong relationships with a handful of cacao cooperatives[6], Goodio both gains visibility

[4]For instance, increased competitive pressures on suppliers to keep prices low have, in part, led to poor labour practices and unsafe working conditions at production facilities. Events such as the 2013 Rana Plaza collapse illustrate the need for increased control by downstream brands to ensure improved, safer labour practices.

[5]We distinguish between transparency and visibility. To create a transparent supply chain requires a company to both gain visibility into its supply chain and disclose information to consumers (New and Brown, 2011)

[6]Cooperatives, particularly in agricultural sectors, are another proven method for ensuring alignment with upstream suppliers. By aggregating smallholder farmers through cooperatives, downstream buyers of goods such as coffee beans (Guijt et al., 2019) and cacao beans (Pilling, 2019) can ensure a

into its supply chain and provides consumers with extensive visibility into the social and environmental impact of its work. Goodio's success in ensuring fair and ethical practices in its cacao supply chain is an example of how smaller, more nimble firms can often be at an advantage when it comes to alignment. In contrast, cacao supply chains within the more mainstream chocolate industry are notorious for poor labour practices and low wages, particularly at the farmer level (de Bassompierre and Jha, 2019). Such larger multinationals often lack visibility into their supply chains because they may manage over 100,000 suppliers. As a result, they often fail to uncover abuses (Webb, 2015).

Many brands and manufacturers acknowledge that they may not have the internal resources or capabilities for extensive visibility. Such companies are increasingly relying on outside support from NGOs/ nonprofits and intermediaries (e.g. cooperatives or supply chain management companies) to ensure the alignment of sustainability practices of upstream suppliers with the overall goals of the supply chain. Consider, for example, the Institute of Public & Environmental Affairs (IPE), a nonprofit based in China. IPE uses publicly available pollution data to map pollution sources and act as an information platform (Russell, 2019; Sustainable Brands, 2018). The data and transparency IPE provide can enable end-to-end alignment by helping companies to monitor and screen both new and existing Tier 1 and Tier 2 suppliers for environmental performance (Plambeck et al., 2012). It can also be leveraged by a broad set of stakeholders, including consumers, activists, and media, to drive environmental improvements in supply chains (MacMahon, 2017). Similarly, a recently announced partnership between Google and WWF Sweden aims to create an open-source "data-enriched decision-making platform" to help firms in the fashion industry understand the environmental impact of their sourcing decisions (Google, 2020). These interactions with third parties can also lead to knowledge-based spillovers that help a brand improve its supply chains' sustainability performance over time (Ramchandani et al., 2020).

End-to-end alignment does not stop at the consumer level. It includes points even further downstream in a supply chain, beyond a product's life cycle. Effective material recovery and closed-loop supply chains require alignment within the reverse supply chain (Gui et al., 2018; Wijnsma et al., 2021) and linking incentives with the forward supply chain (e.g. Agrawal et al. (2015)). For instance, in 2019 Amazon introduced a range of plastic packaging that would help it load more parcels on delivery trucks,

more consistent and high-quality supply, while also gaining assurance that suppliers' practices are sustainable. For farmers, cooperatives not only improve their practices but also provide them with leverage in the marketplace to ensure they receive a higher price and access to a wider range of buyers.

increasing efficiency in its forward supply chain. However, this packaging solution was not recyclable, leading to excessive waste, clogged recycling centers, and heavy criticism from the public (Brignall, 2020).

To avoid a siloed approach to optimisation that undermines the reverse supply chain, Dell closely collaborates with its recycling partners on materials, labeling, and other design choices to determine what features complicate or simplify recycling. This partnership leads to better recycling incentives and higher quality recycled materials. In turn, Dell can reuse this content in its products (Dell, 2020). Considering a product's entire life cycle in this way aligns the complete process, from production to recycling, and increases profits. Similarly, IKEA announced its goal to be fully circular by 2030 and, as a first step, partnered with logistics start-up Optoro to minimise the waste produced in its reverse supply chain.[7] Optoro creates an end-to-end view of reverse-logistics processes using data analytics and machine learning algorithms, which enables IKEA to divert sellable products from landfills back to retail outlets (Forde, 2019).

Alignment requires end-to-end visibility and information sharing. A characteristic feature of sustainable and aligned supply chains is that they secure this alignment through radical transparency that involves all partners in the chain. While Professor Lee actually emphasised this point in his paper, supply chains have made little progress in this direction in the past 16 years. For companies to truly create aligned, sustainable supply chains, there must be a shared understanding and commitment from *all* supply chain entities, including upper-tier suppliers, consumers, and the reverse supply chain.

2.3 How to Facilitate the Development of a Sustainable Triple-A Supply Chain

Based on our reframed definition of triple-A supply chains to incorporate sustainability demands, we next discuss ways to facilitate development of a sustainable triple-A supply chain and the challenges companies may face in achieving this goal. We summarise the recommendations that emerge from the new definitions of the three constructs in Table 2.2.

[7] For further discussions on circularity, we refer readers to Tse et al. (2016) and Agrawal et al. (2019).

Table 2.2 Recommendations to Incorporate Sustainability

	Recommendations
Agile	• Visibility into (activities of) upper-tier and reverse supply chain to ensure quick response to sustainability or compliance incidents • Leverage technology to achieve instant insight into products and partners
Adaptable	• Rethink processes to improve control of supply chain (with or without ownership) • Define business models with sustainability as an input into the organisation's long-term operational planning and corporate strategy
Aligned	• Visibility into (activities of) upper-tier and reverse supply chains to align goals/incentives and avoid sustainability or compliance incidents elsewhere in the chain • Leverage technology to remove barriers between supply chain partners

First, *establishing and maintaining a sustainable triple- A supply chain requires a firm to innovate and rethink its processes.* Doing so can help companies to better adapt and control their supply networks. As discussed in Section 2, Taylor Guitars improved the sustainability practices in its ebony wood supply chain by vertically integrating, and the Haiti Hope project enhanced farmers' livelihoods and the quality of products sourced by Coca-Cola by reinventing the mango supply chain in Haiti. Note that a company does not have to own part of a supply chain to control it better. For example, in the late 2000s, Patagonia reduced its number of suppliers by 50% to gain more oversight of its supply chain and strengthen individual relationships (Patagonia, 020a). Similarly, companies can leverage their sourcing policies to gain better control of suppliers' sustainability practices (Agrawal and Lee, 2019).

Innovation opportunities are not restricted to the forward supply chain. For example, Dell leveraged its closed-loop recycling knowledge to create a new supply source: upcycled ocean-bound plastics. Relatedly, circular economy models build on closed-loop supply chain foundations to rethink business models and connect forward and reverse operations. Consider the multi-retailer LOOP initiative, which was launched in 2019 by recycler TerraCycle. LOOP reinvents the shopping process by re-introducing reusable packaging and the milkman model; it offers shoppers the opportunity to reduce their carbon footprint and waste production by providing products in packaging that can be returned and refilled.

Second, to monitor and improve supply chains' sustainability performance, *companies must gain better visibility into the activities of upper-tier suppliers and reverse supply chains.* Such a change can help align the supply chain's objectives and increase the firm's capacity for agility. It is not enough for companies to rely solely on audits of first-tier suppliers to monitor supply chain activities. There is a growing sentiment that audits alone are not a strong enough tool to reveal what is occurring in a supply chain (e.g. Plambeck and Taylor (2016)). In addition, sustainability incidents are often located not with the first-tier suppliers but with the upper-tier suppliers and the reverse supply chain. To make audits more effective, companies must find ways to extend their efforts further upstream and downstream in the supply chain (like Patagonia has done). Such extension may involve, for example, scaling auditing practices through partnering with competitors (Caro et al., 2018) or nonprofits on joint or shared audits. Approaches beyond auditing are also necessary and may include working with outside parties such as nonprofits or cooperatives to monitor and improve suppliers' practices. In some instances, firms may need to collaborate with competitors and industry partners to establish industry consortiums. For example, Dell initiated NextWave Plastics, an industry consortium dedicated to creating a global supply network for ocean-bound plastics. Besides bringing leading companies together to ensure demand for recycled plastics, the initiative also focuses on visibility by encouraging members to share and replicate best practices (Anupindi and Hoffman, 2018).

Another tool for improving visibility is properly applied technology. Technologies such as blockchain (Smith, 2018) and the Internet of Things (IoT) (Ellen MacArthur Foundation, 2016) can provide consumers and companies with instant insight into, for example, whether a product meets fair trade certification requirements or when a printer cartridge requires replacement or recycling. Such technologies, however, can still be challenging to adopt, even within a relatively small supply chain. For example, although Goodio emphasises radical transparency, it failed to implement blockchain technology to trace raw materials and money in its supply chain. This failure was due to the fact that blockchain, like many technologies, requires full participation from all supply chain stakeholders—in this case, including small farmers with no technical background—in order to work.

It becomes clear, then, that technology is not a quick fix: *leveraging technology to ensure more sustainable supply chains still requires companies and stakeholders to innovate.* Without innovation, barriers may exist between supply chain partners, which cause misalignment of interests and make it difficult to improve a supply chain's sustainability performance. For example, consider GreenBlue, an environmental nonprofit dedicated to increasing transparency related to the chemicals and substances used in products and supply chains (Karaer et al., 2017). In its work, the organisation needed to tackle intellectual property (IP) issues, which pose a significant barrier to transparency.

Suppliers are often reluctant to disclose their products' chemical and material makeup to buyers lest they reveal commercial secrets and lose their competitive advantage. To overcome this barrier, GreenBlue built an innovative platform called Material IQ (MiQ), which allows upstream suppliers and downstream buyers to share sensitive chemical toxicity information without divulging IP secrets. Suppliers submit sample products to SciVera, a GreenBlue partner and third-party chemical safety assessment provider. SciVera then evaluates and scores the product's chemical makeup and the associated risks. This information becomes part of MiQ, so buyers who subscribe to the platform can view the potential hazards of the product. Yet, since they cannot see enough information to reverse engineer the product, the supplier's IP remains protected.

Finally, another challenge to creating a sustainable supply chain is *the lack of defined business models for motivating brands to become more sustainable and align their supply chains with this goal.* Most of the examples we discussed in Section 2 highlight forward-thinking companies, such as Taylor Guitars, Dell, and Patagonia, which took initiative on their own to make their supply chains more sustainable. Such efforts are more the exception than the rule, with many companies still treating sustainability as an operational constraint. Further incentives are needed to ensure that (i) price and quality are not the only drivers of supply chain performance, (ii) brands take responsibility for their entire supply chains, and (iii) sustainable practices and information are shared freely between supply chain partners. As regulations are often uncertain, highly dependent upon politics, enacted very slowly, or oriented more toward stopgap measures than to long-term change, they can be unreliable and limited in their ability to drive foundational changes within industries. Instead, any shift toward sustainability in the mindset of a company or industry will require commitment from the organisation's leadership and a view that sustainability is not just a standard to be met but is rather an essential input into the organisation's long-term operational planning and corporate strategies. Such a change also means that when a company makes sustainability-related decisions, it should reach beyond the bottom line and customer demands to consider new market opportunities and a broader set of stakeholders.

2.4 Conclusion and Future Research Directions

In this paper, we revisit the definitions of agile, adaptable, and aligned supply chains in light of the additional capabilities needed for social and environmental sustainability. To create a sustainable triple-A supply chain, companies must broaden their customer-centric approach to agility by incorporating a more diverse set of stakeholders, including activists, regulators, and employees. Firms should also innovate and adapt their processes by developing new ways to take more control of their supply chains, which can help mitigate compliance and reputation risks and potentially create new market opportunities. Finally, enabling a sustainable triple-A supply chain requires alignment, meaning that there is a shared understanding and commitment from *all* entities in the supply chain, including upper-tier suppliers, consumers, and the reverse supply chain. As such, visibility and transparency are vital to ensuring alignment of sustainability goals across the extended supply chain.

There are many opportunities for operations management research on sustainable triple-A supply chains. For example, while substantial research on *the reverse supply chain* has focused on reverse logistics (e.g. Dekker et al. (2013)) and product design choices (e.g. Gui et al. (2018), Huang et al. (2019)), many of these works are cost-driven and process-focused (e.g. on the collection process). Opportunities, therefore, exist to apply the same exploratory questions used to examine the forward chain to reverse contexts, which will help researchers better understand what is needed to create a sustainable triple-A reverse supply chain. Potential research topics include responsiveness to social and environmental responsibility violations as well as to demand disruptions in the secondary market (*agility*), developing structural hierarchies (e.g. integration, control, or delegation) for waste management services (*adaptability*), and creating transparency and improving coordination through audits and technologies such as blockchain (*alignment*).

The reverse supply chain must also be studied in conjunction with the forward chain. Alignment of forward and reverse supply chain decisions could be aided by research that studies the interactions between up- and downstream agents, such as suppliers, manufacturers, consumers, collectors, and recyclers. Such work would further illustrate the agility required for the reverse supply chain to support the forward chain. Research into the reverse supply chain would also deal with closed-loop business models and frameworks, which are necessary for sustainable triple-A supply chains (e.g. Agrawal et al. (2019), Ferguson and Souza (2010), and Souza (2013)). An examination of business models that connect the forward and reverse supply chains would guide the structural and infrastructural changes required for circularity. These models could help to map potential conflicts between chain partners, which can undermine alignment, and trade-offs between sustainability goals, which can inhibit agile responses to different stakeholder demands.

As discussed in Section 3, establishing and maintaining a sustainable triple-A supply chain requires a firm to gain a deeper understanding of the issues occurring in *the upper tiers of its supply chain.* Monitoring and engaging with upper-tier suppliers in a global supply chain is difficult and requires extensive effort on a brand's part, and the associated resource requirements cannot be understated. The challenge for companies is then to find ways to either gain control of monitoring and engagement activities or formulate innovative ways to delegate them. While a growing body of work investigates sustainability issues in multi-tier contexts from both empirical (e.g. Soundararajan and Brammer (2018), Wilhelm et al. (2016)) and analytical modeling approaches (e.g. Huang et al. (2020), Karaer et al. (2020), and Zhang et al. (2020)), more research on multi-tier supply chains is needed.

From an upstream perspective, opportunities exist to examine collaboration between horizontal competitors (e.g. industry associations), disruptive supply chain design innovations (e.g. vertical integration), and innovative ways to improve suppliers' capabilities. Downstream, a broader study of the role consumers play in sustainable triple-A supply chains could help to further illustrate the link between sustainability practices and market performance. Both of these perspectives could then help to shed light on adaptability issues in sustainable supply chains.

The study of the extended supply chain should not be limited to buyer and supplier interactions. Highlighting the role of external stakeholders such as nonprofits and regulators in shaping the sustainability performance of upper-tier suppliers would provide the operations management literature with a more holistic view of sustainable supply chains. Such work would also help to illustrate the new forms of agility necessary to maintain a sustainable supply chain.

Finally, we identified *increased transparency* as critically necessary for improving the sustainability performance of supply chains. Creating a transparent supply chain requires a company to gain visibility into suppliers' practices and disclose to consumers what is happening in its supply chain (Sodhi and Tang, 2019). The study of disclosing sustainability information and making it public is an emerging topic within the operations management literature (e.g. Buell and Kalkanci (2021), Buell et al. (2019), and Kalkanci and Plambeck (2020)). Still, opportunities exist to understand this dynamic further. For example, it would be valuable to study how technologies like blockchain influence consumers' awareness of and preferences for sustainability. Conversely, testing the implications of disclosure on upstream suppliers' decision making could provide helpful insights into suppliers' behaviours and motives.

Visibility has also become an important topic in the sustainable operations management literature. Research has examined ways to increase visibility into supply chains and make decisions under incomplete visibility (Caro et al., 2018; Chen and Lee, 2017; Kraft et al., 2020; Plambeck and Taylor, 2016). Improved visibility can help align the sustainability goals of a supply chain, increase a firm's agility and improve its response to incidents, and enhance a firm's ability to adapt and innovate processes in its supply chain. While technology and digitisation can improve visibility and transparency, technology adoption within supply chains may be slow and incomplete. Thus, research on how to accelerate the adoption of technologies to improve supply chains' sustainability performance would be useful. Such work could investigate various operational challenges such as heterogeneous users (e.g. brands and farmers), critical mass requirements, and user incentives.

Professor Lee's landmark work on triple-A supply chains has influenced researchers, curricula, and practicing managers worldwide. The concepts he introduced 16 years ago remain valid and valuable in tackling supply chain challenges. We build on his work by revisiting the definitions of agility, adaptability, and alignment in a nuanced way that considers the new demands of social and environmental sustainability. By combining the original definitions with a broader set of stakeholder pressures, innovative approaches for developing and controlling supply sources, and an expanded view of alignment, the triple- A supply chain concept can provide a framework that helps firms tackle the growing challenges that sustainability and circularity present to their supply chains. Accordingly, sustainable triple-A supply chains will create opportunities for new research directions in the operations and supply chain management literature.

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Chapter 3

Treat, Dump, or Export? How Domestic and International Waste Management Policies Shape Waste Chain Outcomes

To minimise the negative impact of unwanted waste disposal methods such as dumping and export, policymakers have implemented laws and regulations designed to combat them. Even so, violations are rampant as a high degree of heterogeneity between firms and proprietary information render monitoring imperfect. Decentralised waste disposal chains, a common form of inter-business organization in this sector, compound this problem as firms also have limited information available on the other waste chain partner, which creates complex interactions between firm behaviour and policy interventions. Against this background, we analyse the effects of domestic and international waste regulations targeting dumping and export, respectively, on firm incentives and compliance. We develop a two-tier waste chain with a manufacturer that generates waste and an operator that treats it. The manufacturer's waste quality and the treatment operator's efficiency are private information. Both can avoid compliance cost by violating regulations where the manufacturer can arrange for the export of the waste and the operator can dump it. We characterise equilibrium waste outcomes and examine the impact of the regulatory climate. Our analysis reveals that primarily focusing on penalizing dumping by treatment operators can worsen waste chain outcomes. Solely focusing on penalizing low-quality waste exports, a common intervention in practice, can also backfire. Instead, penalizing manufacturers for downstream dumping should be given consideration. In addition, the asymmetry

in export burden between waste quality levels should be reduced, which improves both waste outcomes and treatment operator profits.

3.1 Introduction

Every year, millions of tons of waste are generated during manufacturing processes or post-use, much of it containing hazardous materials. The preferred option for dealing with this waste is treatment. This includes processing and separating valuable components, breaking down or immobilizing hazardous substances that cannot be recovered prior to safe and legal landfill disposal, and ultimately recycling or re-refining the materials where possible (e.g. EU Directive 50625-1 and US Title 40 CFR-Subchapter 1 (part 268)). In the European Union and US, regulations prohibit firms from land disposal of untreated hazardous wastes to protect the environment and public health (Bourguignon, 018a; EPA, 2001). In some parts of the world, such as the EU and some US states, manufacturers now also have responsibility for the proper management of their end-of-life products (e.g. ensuring specific targets for treatment such as recovery, re-manufacturing, and recycling are met for products they originally put on the market), following the enactment of Extended Producer Responsibility (EPR) regulations. Moreover, Waste Shipment Regulations prohibit the trans-boundary movement of hazardous wastes to non-EU countries ('Basel ban') and ban the export of any kind of waste for purposes of disposal (Geeraerts et al., 2015).

Nonetheless, investigations have revealed that firms can be inclined to violate regulations when this is more profitable than following them (Europol, 2017; Rucevska et al., 2015). This is particularly relevant for wastes or products containing hazardous content, for which disposal or treatment standards are much stricter and meeting those standards is more costly, such as waste oil, batteries, and certain electronic wastes (e-waste) (Geeraerts et al., 2015). Violations largely take one of two forms: Export or dumping. For example, in 2020, the Dell takeback program was caught for the third time exporting e-waste in violation of the importing country's laws and Dell's own corporate policy (BAN, 2020). Globally, it is estimated that 75% of e-waste is exported, predominantly from the EU and US to developing countries (where labor is cheaper and recycling less regulated), often illegally through mis-classification, bribery, or document forgery (EnviCrimeNet, 2015; UNODC, 2013). Even when waste remains in the country of origin, it is not guaranteed to find proper treatment and may be dumped. For instance, in 2015, Georgia-based Diversified Recycling, with exclusive contracts with major electronics firms, illegally dumped truckloads of toxic waste at a landfill designed to only handle non-toxic construction materials (BAN, 2016). Within the EU, only a little over a third of e-waste is recycled in line with the Waste Electrical and Electronic Equipment directive, which is the bloc's EPR implementation (Eurostat, 2018). It is also estimated that 25% of industrial waste oil is illegally dumped or burned in the EU due to the high cost of treatment for operators (Bourguignon, 2015). Illegal dumping is observed in other waste categories, too. For example, in 2017, directors of Churngold Recycling Ltd. were caught having dumped 30,000 tons of toxic waste from an automotive factory (BBC, 2017).

In this paper, we seek to understand how the regulatory climate interacts with firms' profits and identify what climate would be most conducive to treatment emerging as the waste chain outcome. By "regulatory climate," we refer to the relative strength of export and anti-dumping regulations and/or enforcement efforts. By "waste chain," we refer to a two-agent value chain consisting of a manufacturer (who generates waste that is subject to these regulations) and a treatment operator (who offers waste management services), when these firms can respond by complying (treatment) or violating regulations (dumping or export). Manufacturers produce waste as part of their manufacturing processes or from end-of-life product obligations (individually or by participating in a Producer Responsibility Organization) and must contract a professional treatment operator for the proper management of that waste (Basel Convention, 2018; European Commission, 2014). Treatment operators are the end-of-the-line service providers in the domestic waste market and undertake waste treatment (including recycling, and recovery).

While many waste products can be transformed into goods with positive value through treatment, if the treatment cost is too high, export or dumping may prove economically more attractive. Therefore, the economics of waste treatment, which depends both on *waste characteristics* and the *sophistication of the treatment operator*, plays an important role in waste chain outcomes.

High-quality waste with no or limited hazardous material (e.g. 'green-listed' waste in the EU) poses relatively few problems for treatment or the environment and can be more easily incorporated as raw materials in the manufacture of new products. In contrast, low-quality and relatively hazardous waste (classified in the EU as 'amber' or 'red-listed' waste and in the US as 'hazardous' or 'acutely hazardous' waste), is subject to stricter environmental and export restrictions compared to higher value (e.g. green-listed) waste (Geeraerts et al., 2015). Moreover, materials recovered from lower quality waste often have a more limited range of uses and are thus sold at lower prices.

For example, an increase in hazardous substances in waste oil from manufacturing processes reduces the value of the re-refined product (UNEP, 2012). The recovery value of e-waste similarly depends on the complex mix of precious metals (‘urban mine’) and hazardous components (‘toxic mine’) (Bourguignon, 2015; Rucevska et al., 2015). For instance, plastics found in e-waste contain different levels of brominated flame retardants. Mixtures with concentrations above 0.1% are amber-listed, have lower net recovery values and need more selective treatment processes than e-waste streams with lower concentrations (European Commission, 2010). Therefore, manufacturers generating low-quality waste typically have to pay more for treatment and can be inclined to minimise compliance costs by arranging for export instead (e.g. by using their own infrastructure, involving waste brokers, shipping companies, etc.) (Bernard, 2015; Interpol, 2009; Noel, 2018). Turning now to the sophistication of treatment operators, we note that these firms are not homogeneous. They use facilities that differ in type, age, quality of maintenance, and technology. The more sophisticated an operator, the more value the firm can extract from treating the waste. This can influence an operator’s incentive to skirt regulations and opt for alternative disposal methods, such as dumping the waste at unlicensed landfill sites or disposal facilities (Ino, 2011; Rucevska et al., 2015).

In practice, waste and treatment operator characteristics are private information and not easily assessed, which significantly reduces the effectiveness of monitoring by enforcement agencies such as Europol (Europol 2017) and complicates waste chain relationships. First, the exact composition of the waste is the manufacturer’s private information (Bernard, 2015; Kellenberg, 2012). For instance, the hazard level of industrial waste such as waste oil depends on the processes that generated it, which is information typically only known to the manufacturer. The exact composition of e-waste products is similarly the manufacturer’s private information, which is also the firm arranging for their treatment under EPR.[1] Imperfect monitoring allows these firms to misclassify hazardous (amber-listed) waste as non-hazardous waste (e.g. green-listed or ‘non-waste’) to avoid export regulations (IMPEL, 2011), but the lack of accurate information on the waste streams is also a pressing problem for treatment operators since the recovery value depends on the waste quality. In practice, it is difficult for operators to ascertain the waste quality even after receiving it, because the instruments

[1]This responsibility can also be delegated to a Producer Responsibility Organization (PRO) that acts collectively on behalf of its member companies to fulfil their EPR obligation. To account for this setting, §3.6.2 relaxes the assumption that the manufacturer has perfect information on the waste composition.

they rely on to do so are known to be inefficient and costly (European Commission, 2014). An operator may therefore face problems formulating a profitable pricing strategy (e.g. one that is differentiated by waste quality) under information asymmetry.

Second, his ability to recover value from a range of waste qualities is the treatment operator's private information as value recovery depends on a complex set of internal capabilities and management practices (Levi and Nault, 2004; Shinkuma and Managi, 2011). Imperfect monitoring allows these firms to illegally dump waste that is not economic to treat. Relying on auditing and/or third-party certification to reduce this information asymmetry and anticipate when dumping may occur is costly and has been largely unsuccessful as even certified companies are frequently found to engage in non-compliant behaviour (Europol, 2017; Rucevska et al., 2015). This is problematic for manufacturers since policies like EPR expect them to ensure that those they contract with to manage their waste are operating in compliance with regulations (called "duty of care"). Therefore, when a manufacturer needs to contract with a treatment operator whose incentives it cannot adequately assess, the firm faces a dilemma: Is it worth purchasing costly treatment services and risk the waste will be dumped, when exporting is also an option?

Policies to encourage proper treatment to date have focused on regulation and enforcement where non-compliance is likely to occur: Banning the export of hazardous wastes (i.e., focusing on low-quality waste) and fining treatment operators who dump (i.e., focusing on the directly responsible agent). A relatively nascent practice in current EPR implementations is fining the manufacturers who did not meet responsibility requirements when contracting with treatment operators who are later found engaged in dumping (Özdemir et al., 2012). However, the two-sided information asymmetry discussed above creates complex interactions between the regulatory climate and firm behaviours that drive waste chain outcomes (treatment, export, dumping). Therefore, such policies may have unintended consequences that should be better understood. This will benefit agencies like Europol and the EPA in effectively targeting their efforts and companies in advocating for policies that address market failures and avoid disturbing relationships where waste treatment is functioning well. This context frames our two key research questions:

- What are the implications of double-sided information asymmetry between channel partners on waste chain outcomes?
- Where should the legislative and enforcement focus be concentrated so that treatment emerges as the waste chain outcome? In particular, what is the impact

of strengthening domestic anti-dumping measures on either agent and that of strengthening international export policies regarding different waste types?

To date, the relevant literature on waste outcomes has focused on the effect of regulatory differences between countries in single-agent models or complete information markets. A key contribution of our paper is modeling the two-agent waste chain subject to two-sided information asymmetry and analyzing the waste outcomes in this context. To capture the aforementioned compliance and information problems, we develop a game-theoretic model of the waste chain that consists of a manufacturer ("she") who can contract with a local waste treatment operator ("he") under two-sided information asymmetry. The manufacturer is differentiated by waste quality and the treatment operator is differentiated by cost efficiency. We model both the preferred activity (treatment) and illegal or unwanted activities (dumping and export). The manufacturer's non-compliance action is export and the local treatment operator's non-compliance action is dumping. After modeling the economics of the waste chain, we characterise the equilibrium outcomes and compare them to the complete information benchmark. Finally, we evaluate the effects of the international policy climate (stringency level and target waste type of export regulations) and the domestic policy climate (strength and target agent of anti-dumping enforcement) on these outcomes.

We find that information asymmetry can negatively or positively impact compliance through firm interactions and that regulatory stringency plays a decisive role in this outcome. Current regulations that primarily focus on discouraging the export of low-quality waste can backfire and create perverse incentives. Driven by moral hazard and adverse selection, illegal dumping becomes more attractive, prices increase, and the efficient operator's profit is undermined, thereby attaining the opposite of what was intended. Regulating the export of high-quality waste more closely is a powerful tool to avoid this trap by ensuring that the opportunity cost of serving the full waste market compared to only serving the low-end waste market is not too high. We find that efficient operators always benefit from the more stringent regulation of high-quality waste, while inefficient operators only benefit when this regulation is sufficiently stringent. In other words, the incentives of treatment operators are aligned with the imposition of stringent regulations on the export of high-quality waste.

We further find that export regulations on high-quality waste should be complemented by domestic anti-dumping enforcement efforts to ensure the best possible waste management outcome is attained. An increase in the dumping cost for the manufacturer is a particularly effective measure that reduces the manufacturer's willingness to pay when dumping activities occur and can expand the scope of waste treatment. However, such domestic enforcement efforts should be carefully tailored in conjunction with export regulations so that they do not backfire by undermining profits of efficient operators or even worsening waste management outcomes.

The rest of the paper is organised as follows. In §3.2, we present the related literature. §3.3 presents our modeling framework and assumptions. §3.4 analyses the benchmark case of complete information, followed by a detailed analysis of the decentralised waste chain. §3.5 presents the effect of export regulations and their relative stringency between waste categories, as well as the effect of domestic enforcement efforts and their relative strength towards the manufacturer and treatment operator. §3.6 investigates the robustness of our conclusions to relaxing certain assumptions. §3.7 concludes with policy recommendations and directions for future research.

3.2 Related Literature

A stream of research in environmental economics has studied the effect of policy measures on violations in waste disposal. This literature has analysed the incentive structure toward dumping (e.g. Copeland (1991); Fullerton and Kinnaman (1995); Ino (2011); Smith (1972); Walls et al. (2001)) or export (e.g. Baggs (2009); Bernard (2015); Kellenberg (2012)) under imperfect monitoring and the effect of incentive structures on optimal policy measures, including EPR implementations and export regulations. One of the main findings is the pollution haven hypothesis, which stipulates that waste moves to the cheapest disposal option, and to avoid this move, regulatory differences between countries must be reduced (Kellenberg, 2012).

We contribute to this stream of research by capturing the decentralised nature of the waste chain. In particular, we study environmental violations and profit implications driven by interactions between firms along the waste chain under two-sided information asymmetry, whereas the aforementioned literature mainly considers the responses of a single firm or a market with complete information. As a result, we find that the pollution haven hypothesis gives an important albeit incomplete explanation of the violations we see in the market and of policies to address them. In particular, we find that regulatory differences between waste categories must be limited and that the emphasis on primarily regulating low-quality waste can deteriorate waste chain outcomes.

Two exceptions to the single-agent and complete information studies are Shinkuma and Managi (2011) and Kinnaman and Takeuchi (2014). The former article models incentives to dump or improperly treat waste residuals when the waste manufacturer and the government are uninformed about the technological efficiency of the operator. In contrast to our paper, the authors consider a uniform waste quality that is common knowledge. Kinnaman and Takeuchi (2014) focus on how proprietary information on waste quality and operator efficiency lead to intentional and unintentional damages done by a treatment operator and explore how the environmental cost should be allocated to the guilty and innocent party to increase proper disposal, which can be perfectly assessed in their model. In practice, imperfect monitoring generally does not allow authorities to perfectly price environmental damage nor identify share of guilt. We therefore consider the effects of existing interventions that do not rely on this assumption. Moreover, we endogenise the treatment price and incorporate producer responsibility in the form of an expected cost for the manufacturer if the contracted treatment operator is non-compliant (which can be due to legal fees or goodwill loss). We demonstrate that when enforcement agencies and firms cannot perfectly identify the guilty parties, directly enforcing the areas where non-compliance is likely may not be as effective and can even backfire and undermine compliant firms.

Within Operations Management, our research falls within the themes of responsibility violations and the reverse supply chain. To the best of our knowledge, this is the first paper in the literature that studies the effect of environmental regulations on channel interactions in the presence of non-compliance options and two-sided information asymmetry.

Existing research on firm responsibility violations addresses the issue of information asymmetry among decentralised channel partners in traditional supply chains when a supplier can hide non-compliant behaviour. Violations include non-adherence to labor codes such as using child labor or having insufficient safety regulations in place, using polluting practices, or other unethical behaviour (Aral et al., 2014; Caro et al., 2018; Chen and Lee, 2017; Cho et al., 2019; Guo et al., 2016; Kalkanci and Plambeck, 2020; Plambeck and Taylor, 2016; Short et al., 2016). These studies consider the possibilities for manufacturers to reduce information asymmetry by using auditing schemes or publication of supplier lists as opposed to relying on regulatory interventions because suppliers are generally located within developing countries where institutions are weak. In the context of regulatory penalties, Kim (2015) investigates the interplay between regulatory inspections and voluntary, preemptive noncompliance disclosure by a production firm. Levi and Nault (2004) consider government interventions that could induce firms to make a major conversion to cleaner plants and equipment when this is unobserved by policymakers.

We contribute to these studies by incorporating non-compliance in a waste chain when both agents face incomplete information with respect to one another. This is a particularly relevant application as the waste industry is notorious for high non-compliance rates due to the nature of waste being a ‘bad’ rather than a ‘good’. In addition, previous studies considered a single firm that can be non-compliant, often modeled as an exogenous probability, and that holds private information. In contrast, we incorporate double-sided information asymmetry and endogenous non-compliance options and find that this setting can induce adverse selection and additional moral hazard problems. To ensure that both agents comply, a combination of policy options is necessary to combat these market failures and to ensure that waste stays in the formal disposal process.

The second relevant Operations Management stream studies the effect of environmental law and policy making on the interactions between firms in the reverse supply chain. Although research on environmental management in the reverse supply chain has been a growing field (for an extensive review see Agrawal et al., 2019; Corbett and Klassen, 2006; Souza, 2013), there remains a strong need to understand firms’ incentives and the economic impact of waste regulations to avoid unintended consequences of such regulations. One policy that has been extensively studied in operations management is Extended Producer Responsibility (EPR). Huang et al. (2019), Atasu and Souza (2013), Özdemir et al. (2012), and Plambeck and Wang (2009) study manufacturer responses to EPR implementations with respect to product design, while Rahmani et al. (2020) specifically discriminate between recycling technologies to understand potential interactions with product design. Esenduran et al. (2016) study how various levels of legislation affect manufacturing, remanufacturing, and collection decisions. Tian et al. (2019), Gui et al. (2018), Gui et al. (2016), and Atasu and Subramanian (2012) examine producer incentives to participate in collective or individual recycling schemes. Jacobs and Özdemir (2012) explore firm-level interactions and analyse the impact of different allocations of recycling cost between a manufacturer and treatment operator on their profits and incentives to recycle. Subramanian et al. (2009) look at the effect of EPR policy on design and coordination incentives between consumers and manufacturers. Atasu and Souza (2009) and Atasu et al. (2013) consider environmental implications beyond economic impacts of take-back schemes within a system consisting of a regulator, manufacturer, and consumer. Lastly, Esenduran et al. (2019) consider EPR landfill diversion when e-waste recycling is profitable rather than costly.

Our work is aligned with and contributes to this stream of research by identifying how operational decisions and supply chain interactions shape the outcomes of a given environmental policy, sometimes in unintended ways. In particular, we expand on the notion that firms can choose to be non-compliant due to imperfect monitoring by subjecting them to informational limitations, which is yet to be applied to the reverse chain. We therefore differ from existing studies by focusing on the effect of regulations on firm-level interactions and violations when agents operate under incomplete information. One of the key elements of our paper is the effect of the waste chain's information structure on the compliance incentives of the agents. To the best of our knowledge, only two studies have considered information asymmetry between firms in reverse chains, but they do not consider non-compliance options or regulatory interventions (Wei et al., 2015; Zhang et al., 2014). In addition, we consider the responses of both the manufacturer and treatment operator to waste regulations as either agent can impact the economic and environmental outcomes of the waste chain through non-compliance.

3.3 Model Description

We model a two-tier waste chain consisting of a manufacturer (she) and a treatment operator (he). The manufacturer generates waste through manufacturing processes or through end-of-life product obligations. These wastes can be low-quality (e.g. amber-listed waste with high hazard levels) or high-quality (e.g. green-listed waste with no or low hazard levels). The manufacturer either contracts a local treatment operator or exports the waste, legally or illegally, depending on the waste characteristics.[2] If contracted, the treatment operator either dumps the waste domestically or treats it according to the legally required standard.[3] Consequently, waste can end up treated, dumped domestically (by the treatment operator), or exported (by the manufacturer).

[2]Manufacturers can only dispose of their own waste at the place of production if they can show the waste is non-hazardous or treated according to the best available techniques (EU Directive 2008/98/EC). Although dumping (e.g. illegal landfill) does not require the use of these facilities, a manufacturer cannot credibly hide dumping activities without them. Since manufacturers with treatment facilities are rare (European Commission, 2014), we do not include dumping as an option for manufacturers in our model.

[3]Operators can in theory export the waste after they have obtained it, but investigations show that export typically happens before significant costs have been incurred from the waste (e.g. treatment, recycling, and even dismantling due to high labor cost) (Bisschop, 2017; Geeraerts et al., 2015). Thus,

We formulate a three-stage game where the treatment operator sets the treatment price (stage 1), the manufacturer decides whether to contract or to export (stage 2), and the treatment operator (if contracted) decides whether to treat or dump (stage 3). The waste quality and the treatment efficiency are proprietary information of the manufacturer and the treatment operator, respectively, leading to information asymmetry along the waste chain.

In the rest of this section, we present the waste chain model, outline the game in detail, and introduce key parameter assumptions. Table 3.1 summarises our notation.

The waste chain. This chain consists of two actors, the manufacturer and the treatment operator. To capture differentiated waste quality, we consider two manufacturer types, $i = H$ (high) and $i = L$ (low), who generate high- and low-quality waste, respectively. The quality of the waste determines the revenue that can be generated from it using the legally required treatment standard. A batch of high-quality waste (e.g. electronics with high amounts of precious metals, clean waste oil) contains a high reprocessing value, which generates revenue v_H post treatment. A batch of low-quality waste (i.e., waste with higher hazard levels) generates a lower revenue v_L, with $0 \leq v_L < v_H$. The waste quality of a manufacturer can depend on, for instance, the processes the manufacturer employed that generated the waste, the manufacturer's choice of (complexity of) design of the products and whether the firm uses high quality or easily recyclable materials. We assume that the exact quality $i \in \{H, L\}$ is only known to the manufacturer, whereas the prior belief of the treatment operator is that the waste is high-quality with probability h and low-quality with probability $1 - h$, where $h \in (0, 1)$. In §3.6, we look at a generalization by introducing some uncertainty about the waste quality on the side of the manufacturer (e.g. when manufacturers are collectively organised as a PRO and the PRO is the manufacturer in our model).

To capture differentiated treatment efficiency, we consider two treatment operator types, $j = E$ (efficient) or $j = I$ (inefficient). The efficiency of the operator determines the cost c_j the operator incurs if he decides to treat the waste, where treating with the inefficient technology is more costly ($c_I > c_E > 0$). Thus, the net cost of an inefficient operator will be larger than that of an efficient one after treating waste of a given quality, specifically $c_I - v_i > c_E - v_i$.[4] We assume that his efficiency level $j \in \{E, I\}$ is the operator's proprietary information, whereas the prior belief of the manufacturer is

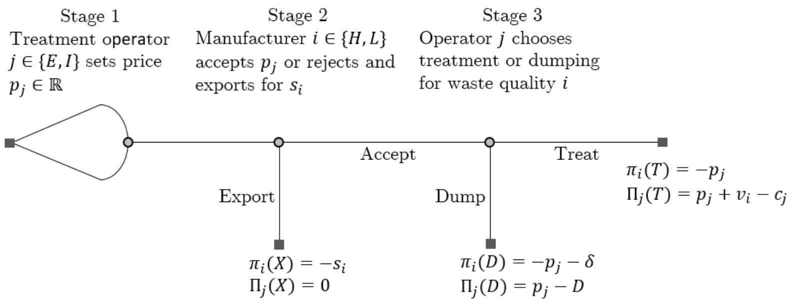
in our model only the manufacturer considers export an option using either its own infrastructure or through third-parties such as waste brokers.

[4]Here we assume that the cost of treatment is independent of waste quality. Alternatively, we can model the cost of treatment as a concave function of waste quality, where a lower waste quality is

that the operator is efficient with probability γ and inefficient with probability $1-\gamma$, where $\gamma \in (0,1)$. We assume that the operator must treat the waste to ascertain its market value v_i, i.e., receiving the waste is not sufficient to find out its quality. The manufacturer and operator characteristics are modeled as exogenous parameters in this waste chain as they depend on previous product design and facility technology investments. In §3.6, we introduce an opportunity for the treatment operator to perform a costly quality check after he has received the waste.

Game specification. Figure 3.1 illustrates the sequence of the agents' decisions and the resulting profits. In the first stage, treatment operator $j \in \{E, I\}$ sets his price $p_j \in \mathbb{R}$ for providing waste management services. According to a European Commission report, operators set the prices for the waste management services which manufacturers can choose to accept (European Commission, 2014). Further evidence that operators have pricing power is provided by the inelasticity of demand for waste management services of potentially hazardous waste. The reason is that the amount of waste treatment required is set by EU legislation and national targets and hence demand is insensitive to the price (Baird et al., 2014; Van Daele et al., 2007). Therefore, in our model, we assume a sequential game where the operator moves first and sets the price, after which the producer responds. Without loss of generality, we assume a standard batch size with the price quoted accordingly (waste services are typically priced by weight).

Fig. 3.1 Waste Chain: Timing and Profits of Three-Stage Game



In the second stage, the manufacturer $i \in \{H, L\}$, who is in the market for waste management services, can either purchase the service at the quoted price or decide to export her waste at the cost of s_i. Exporting low-quality waste comes with an additional cost relative to high-quality waste, for example due to the need to comply

more costly to treat. This yields the same qualitative results since, for a given waste quality, Operator I will incur strictly higher cost: $c_I(v_i) > c_E(v_i)$.

with or evade more stringent export, environmental, reporting, and safety regulations (e.g. Waste Shipment Regulations in the EU). To capture this, we assume $s_L > s_H$. The local operator is not involved in case of export and will have zero profit.

At the last stage, the manufacturer has contracted the services of the local treatment operator j for price p_j. After obtaining the price and receiving the waste, the operator decides whether to treat or dump. By treating, his profit is $\Pi_j(T) = p_j + v_i - c_j$: the price p_j minus the net cost of treatment $(c_j - v_i)$, which depends on the waste quality and his efficiency, while the manufacturer profit is $\pi_i(T) = -p_j$. The treatment operator may avoid the cost of treating altogether by dumping the obtained waste instead. In this case, local authorities may discover the violation, resulting in fines and reputation cost. We assume the repercussions will cost the operator $D \geq 0$ in expectation, leading to a profit of $\Pi_j(P) = p_j - D$. Moreover, the violation may be traced back to the manufacturer, who will suffer fines or goodwill loss as she did not fulfil her waste disposal responsibility. We assume this will cost her $\delta \geq 0$ in expectation, hence her profits are $\pi_i(P) = -p_j - \delta$.

Table 3.1 Key Notation

	Manufacturer $i \in \{H, L\}$
π_i	Profit of the manufacturer
s_i	Expected cost to export, where $s_L > s_H$
h	Manufacturer's prior probability that $i = H$
δ	Expected cost of reputation loss and fines incurred by manufacturer when the contracted treatment operator dumps
	Treatment Operator $j \in \{E, I\}$
Π_j	Profit of the treatment operator
p_j	Treatment price charged by Operator j, where $p_j \in \mathbb{R}$
c_j	Expected cost of treatment, where $c_E < c_I$
γ	Treatment Operator's prior probability that $j = E$
v_i	Expected recovery value of waste, where $v_H > v_L$
$\overline{v}$	Average recovery value of waste, where $\overline{v} = hv_H + (1-h)v_L$
D	Expected cost of reputation loss and fines incurred by operator when he dumps

The cost parameters associated with export and dumping implicitly capture the combined effect of regulatory stringency and enforcement effort on the two agents. Where regulation is still evolving, as in international export, we will primarily refer to regulatory stringency as the lever for change, and where regulation is more established, as in domestic dumping, we will primarily refer to enforcement effort as the lever for change.

Assumptions. We make some assumptions in order to focus on markets where there is an incentive to deviate from compliance, but not regardless of waste quality or facility efficiency.

Assumption 1. (i) $D \geq c_E - v_L$; (ii) $D < c_I - v_L$; (iii) $D \geq c_I - hv_H - (1-h)v_L$.

Assumption 1 ensures that we consider a meaningful market where dumping is not the default option. In particular, the operator dumps when he is inefficient if and only if he believes that he received low-quality waste. When the operator is efficient, he treats the waste regardless of its quality. To see this, note that at the third stage, Operator j chooses between treating or dumping in order to maximise his profit, depending on the value of the waste after treatment (Ino, 2011). If the net cost of treating is less than the expected cost of dumping (i.e., $c_j - v_i \leq D$), the operator chooses to treat and be compliant, otherwise he prefers to dump. Condition (i) ensures that the efficient operator E is better off treating the waste, regardless of its quality, since $v_H > v_L$. Condition (ii) ensures the inefficient operator is better off dumping low-quality waste. Condition (iii) ensures that if Operator I is contracted at $t = 2$ but is uncertain about the quality of the waste he receives (prior belief h), he will prefer to treat at $t = 3$.[5]

Assumption 2. (i) $s_H \geq c_I - v_H$; (ii) $s_L \geq c_E - v_L$.

Recall that the manufacturer's outside option is to export at cost s_i, so she is not willing to incur more cost than this for local waste management services. Assumption 2 ensures that – provided the operator intends to treat at $t = 3$ – there exists a price where the manufacturer is better off getting her waste treated and the treatment operator can make a positive profit. In other words, it is efficient to treat the waste locally. Condition (i) ensures this for the high-quality waste regardless of the treatment operator type receiving it, while condition (ii) ensures it for the efficient treatment operator receiving low-quality waste.[6]

Market failures. Two types of market failures often arise as a result of incomplete information: adverse selection and moral hazard. In our model, the manufacturer has a non-verifiable, non-contractible waste quality. Therefore, there exist prices for which both manufacturer types will purchase the waste management service, as well as prices that only the low-quality type will accept. Choosing a price from the latter range induces adverse selection as only the low-quality manufacturer type would accept it

[5]Note that for the complete information case, we can use a weaker assumption $D \geq c_I - v_H$ which stipulates that the inefficient operator treats if he faces high-quality waste with certainty.

[6]Since Operator I would dump the waste of Manufacturer L, we do not make an assumption for that case.

(thus revealing her type to the operator). Moral hazard emerges when the operator dumps the waste even if the manufacturer prefers treatment. We find that with incomplete information, moral hazard can become more problematic. Specifically, the inefficient operator might select to dump the waste after receiving it, but it will not be possible for the manufacturer to identify this behaviour a priori if both operator types pool on price.

3.4 Analysis

We start by presenting the complete information benchmark in §3.4.1, where we solve the model introduced above for perfect Nash equilibria. We then analyse the equilibria under two-sided information asymmetry in §3.4.2 under weak and strong domestic anti-dumping enforcement efforts, relative to the strength of export regulations. All proofs are provided in the Appendix.

3.4.1 The Complete Information Benchmark

We start by analyzing the benchmark case where the manufacturer and the treatment operator are informed about each other's type.

Lemma 1. *Under complete information, treatment is the equilibrium outcome except if the waste is low quality (L) and the treatment operator is inefficient (I). In that case, waste is locally dumped for $D + \delta \leq s_L$ and exported otherwise.*

The equilibrium characterization in Lemma 1, the corresponding prices, manufacturer's profit, and operator's profit can be found in Table 3.2.
As a consequence of Assumptions 1 and 2, under complete information, waste is treated when it is of high-quality (last column) or the treatment operator is efficient (last row). In other words, enforcement is irrelevant for high-quality waste since both operator types have an incentive to treat it for a price that is acceptable for the manufacturer ($p_j^B = s_H$). It is also irrelevant when an operator is efficient, because his treatment cost is sufficiently low to treat waste profitably regardless of its quality.

When a low-quality waste manufacturer contracts with an inefficient treatment operator, the operator can dump the waste regardless of the manufacturer's preferences, creating a moral hazard problem. Manufacturer L understands that Operator I would dump the waste if he gets it, leading to an overall expected expenditure of $p_j + \delta$. Since export costs s_L, her maximum willingness to pay for the services of Operator I is $s_L - \delta$. Thus

Table 3.2 Complete Information: Equilibrium Prices and Profits

	Waste Quality L		Waste Quality H
	Weak domestic enforcement $D+\delta \leq s_L$	Strong domestic enforcement $D+\delta > s_L$	Any enforcement
Facility I	**Dump** $p_I^B = s_L - \delta$ $\pi_L^B = -p_I^B - \delta$ $\Pi_I^B = p_I^B - D$	**Export** $p_I^B > s_L - \delta$ $\pi_L^B = -s_L$ $\Pi_I^B = 0$	**Treat** $p_I^B = s_H$ $\pi_H^B = -p_I^B$ $\Pi_I^B = p_I^B + v_H - c_I$
Facility E	**Treat** $p_E^B = s_L$ $\pi_L^B = -p_E^B$ $\Pi_E^B = p_E^B + v_L - c_E$	**Treat** $p_E^B = s_L$ $\pi_L^B = -p_E^B$ $\Pi_E^B = p_E^B + v_L - c_E$	**Treat** $p_E^B = s_H$ $\pi_H^B = -p_E^B$ $\Pi_E^B = p_E^B + v_H - c_E$

Note. Each cell includes the following information about the equilibrium: (i) waste management outcome: Treat, Dump, or Export, (ii) the price p_j^B offered by the treatment operator, (iii) the profit of the manufacturer π_i^B, and (iv) the profit of the operator Π_j^B.

two possible equilibrium outcomes can occur. When the operator's dumping cost is lower than the manufacturer's maximum willingness to pay, i.e., $D < s_L - \delta$, Operator I sets the highest price that Manufacturer L would accept, $p_I^B = s_L - \delta$, obtains the waste, and then dumps it. If $D > s_L - \delta$, then any price acceptable to Manufacturer L would lead to a negative profit for Operator I thus he sets his price higher than the manufacturer's willingness to pay and the manufacturer prefers to export. Hence, higher domestic enforcement levels $(D + \delta > s_L)$ can replace the moral hazard problem that leads to dumping with export. We call this the "*displacement effect*". Conversely, strengthening export regulations $(D + \delta \leq s_L)$ can retain low-quality waste in the local market but does not guarantee its proper treatment due to moral hazard. A clear example of the former case is seen for e-waste where most EU member states have a strong regulatory climate against domestic e-waste dumping, making export, even when it is illegal, an attractive option (EnviCrimeNet, 2015).

These findings are consistent with the pollution haven hypothesis, which stipulates that waste moves to the cheapest disposal option (Kellenberg, 2012). In this case, we see that domestic and/or international enforcement efforts may not eliminate non-compliant behaviour but merely relocate the waste between local dumping and international export.

3.4.2 Two-sided Information Asymmetry

In this section, we analyse the effects of information asymmetry in a decentralised waste chain where outcomes are impacted by moral hazard and adverse selection. Specifically, the chain is composed of a treatment operator who is uninformed about the waste quality he receives from the manufacturer and a manufacturer who is uninformed about the operator's efficiency. Consequently, the operator is unable to discriminate between valuable (H) and less valuable (L) waste. In practice, this means that operators cannot easily tailor p_j to the waste quality. Moreover, the manufacturer cannot assess whether the operator's facilities are efficient enough to profitably treat waste L, and thus might end up paying a higher price to an operator that dumps than she would have been willing to under full information. The result is that treatment operators can be paid to treat the waste while in fact dumping it (Rucevska et al., 2015).

We find that these complications result in three types of equilibria, which we call the Breakdown, Full Compliance and Partial Compliance equilibria. We first describe these equilibria in more detail and discuss when they emerge depending on the stringency of international export regulation (s_L, s_H) and the strength of domestic anti-dumping enforcement (D, δ). These conditions will be useful later on when discussing the impact of changing export policies and anti-dumping efforts. We solve the model for perfect Bayesian Nash equilibria. When equilibrium multiplicity arises, we apply the undefeated equilibrium refinement developed by (Mailath et al., 1993) that is well-suited for signaling games with double-sided information asymmetry. If multiplicity remains, we select the non-Pareto dominated equilibrium, if such an equilibrium exists. When there exists a unique equilibrium that is non-Pareto dominated and undefeated, we refer to this equilibrium as *the unique* equilibrium and when it coexists with other undefeated, non-Pareto dominated equilibria, we refer to it as *an* equilibrium in the propositions. In §3.4.2, we focus on the case of a weak domestic anti-dumping enforcement climate compared to the export regulation climate, and proceed in §3.4.2 to analyse how stronger anti-dumping enforcement impacts equilibrium outcomes.

Weak domestic enforcement

In this section, we explore the equilibrium outcomes when the aggregate of the domestic anti-dumping enforcement efforts are weak relative to the export regulations, i.e., $D + \delta \leq s_L$. In the benchmark case, these conditions result in waste treatment in all cases except when waste L reaches Operator I, when dumping would occur.

Breakdown Equilibrium: In this equilibrium, treatment only survives in the Manufacturer L - Operator E pairing (Table 3.3). Both treatment operator types pool on a price p^* that is higher than the willingness to pay of Manufacturer H, creating an adverse selection and moral hazard problem. The high-quality waste is exported because this is cheaper for the manufacturer. Due to this adverse selection problem, the type of the waste that remains domestically is revealed to be low quality. Consequently, Operator I will dump it. This is called moral hazard since the operator is paid for appropriate treatment but dumps the waste as this is more profitable than treatment. Due to the pooling price, Operator I is indistinguishable from Operator E for the manufacturer. Manufacturer L's maximum willingness to pay for waste management services is therefore weighed by her belief about whether the operator is inefficient (i.e., $1-\gamma$). The maximum price either operator can charge without inducing Manufacturer L to export is therefore $p^* = s_L - (1-\gamma)\delta$. Due to incomplete information, Operator E obtains a lower price than he did in the complete information benchmark ($p^* < p_E^B$) for low-quality waste. This loss is effectively transferred towards the profit of Operator I, who benefits from the compliant behaviour of the other operator type ($p^* > p_I^B$). The result is a perfect Bayesian Nash equilibrium in which both operator types pool on price but separate on disposal method. We formalise these findings in Proposition 1 and summarise them in Table 3.3.

Table 3.3 Prices and Profits in Breakdown Equilibrium when $D + \delta \leq s_L$

Breakdown			
	Waste Quality L	Waste Quality H	Price
Inefficient Facilities I	**Dump** $\pi_L = -p^* - \delta$ $\Pi_I = p^* - D$	**Export** $\pi_H = -s_H$ $\Pi_I = 0$	$p^* = s_L - (1-\gamma)\delta$
Efficient Facilities E	**Treat** $\pi_L = -p^*$ $\Pi_E = p^* + v_L - c_E$	**Export** $\pi_H = -s_H$ $\Pi_E = 0$	

Note. Each cell includes the following information about the equilibrium: (i) waste management outcome: Treat, Dump, or Export, (ii) the pooling price p^* offered by the treatment operator, (iii) the profit of the manufacturer π_i, and (iv) the profit of the operator Π_j. In contrast to the complete information benchmark, waste H is exported rather than treated.

Proposition 1. *When $D + \delta \leq s_L$, in the Breakdown equilibrium, both operator types pool on $p^* = s_L - (1-\gamma)\delta$. Manufacturer H exports and Manufacturer L contracts the local treatment operator. Finally, Operator I dumps while Operator E treats the waste he receives.*

Breakdown is the unique equilibrium[7] *if and only if*

$$s_H \leq h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta). \tag{Bd}$$

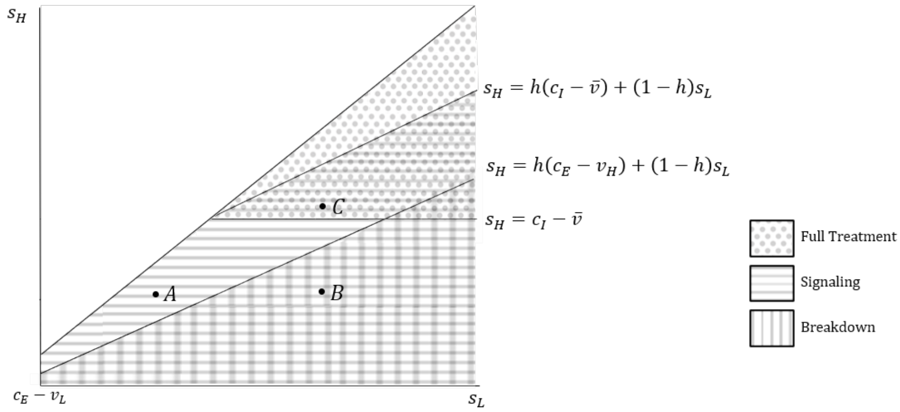
A necessary condition for the Breakdown equilibrium is $s_H \leq h(c_E - v_H) + (1-h)s_L$.

The necessary and sufficient condition is expressed in terms of both the export parameters (s_L, s_H) and domestic enforcement parameters (D, δ), which will inform our results on domestic enforcement and its interplay with international policy. The necessary condition is expressed in terms of the parameters capturing only the export policies (s_L, s_H), which allows us to distill insights on the role of the international policy climate.

To understand these conditions, recall that a high export cost increases the manufacturer's willingness to pay for local waste management services. The necessary and sufficient condition (Bd) ensures that Operator E prefers to induce adverse selection with $p^* = s_L - (1-\gamma)\delta$ and only acquire the waste when it is low quality (expected profit $E\Pi_E = (1-h)(p^* + v_L - c_E)$) to deviating to price $\tilde{p} = s_H$, which would lead to treating any waste type (expected profit $E\Pi_E = \tilde{p} + \overline{v} - c_E$), i.e., when $(1-h)(s_L - (1-\gamma)\delta + v_L - c_E) \geq s_H + hv_H + (1-h)v_L - c_E$. This inequality can be rewritten as (Bd), which serves to illustrate that all else being equal, the export cost of high-quality waste must be small relative to the cost of its low-quality counterpart. Second, the necessary condition corresponds to setting $\delta = 0$ in (Bd), which is the condition that must hold for the breakdown equilibrium to emerge when the manufacturer suffers no penalty if her waste is dumped. Here, the export cost of high-quality waste must again be small relative to that of low-quality waste, but less so than when $\delta > 0$. The necessary condition for the Breakdown equilibrium is illustrated in the vertically shaded bottom part of Figure 3.2, which displays the necessary conditions for each of the equilibria, with the export costs of the low- and high-quality waste on the axes.
Thus, in a Breakdown equilibrium, the waste outcome strictly deteriorates compared to the complete information benchmark due to adverse selection, which directs high-quality waste to export. In addition, compared to the benchmark, the compliant operator's profits are strictly lower. First, he misses out on the high-end market due to adverse selection. Second, the price he receives for low-quality waste is strictly lower ($p^* < p_E^B$) since, due to moral hazard, Operator I dumps the waste and the manufacturer cannot distinguish between the two types of operator. The non-compliant operator also misses out on the high-end market but in fact benefits from the information asymmetry and achieves a higher price for low-quality waste than in the benchmark case ($p^* > p_I^B$).

[7] Recall that this means it is the unique non-Pareto dominated and undefeated equilibrium.

Fig. 3.2 Equilibrium Necessary Conditions as a Function of Export Regulations



Note. This figure is plotted for $0 < c_E - v_L \leq c_I - \overline{v}$. For other conditions on $c_E - v_L$ and $c_I - \overline{v}$, the regions may vary in size. Per Assumption 2, $s_L \geq c_E - v_L$.

Under some conditions, this can even offset the losses from the high-end market such that Operator I can be better off in Breakdown than in the benchmark case. Therefore, the manufacturer's inability to distinguish between non-compliant and compliant operators undermines the legitimacy of waste management services, undervaluing the services of compliant operators and benefiting those that violate regulations. This problem occurring when moral hazard is combined with asymmetric information is consistent with what law enforcement agencies have found in practice (Europol, 2017; Rucevska et al., 2015). From a policy point of view, this equilibrium can be considered as worse than the others.

Full Compliance Equilibrium: In the Full Compliance equilibrium, waste is treated regardless of its quality and the efficiency of the operator (Table 3.4) and neither moral hazard nor adverse selection is observed. To attain this equilibrium, the operator must be willing to set his price equal to the lowest willingness to pay in the market $p^* = s_H$ regardless of his type, since any higher would induce Manufacturer H to export her waste. The manufacturer purchases the offered treatment service regardless of her type, resulting in an expected waste quality of $\overline{v} = hv_H + (1-h)v_L$. Recall that per Assumption 1 (iii), both types of operator treat the waste under the prior uncertainty. The expected profit of the operator is $E\Pi_j = s_H + \overline{v} - c_j$ and the manufacturer's profit is $\pi_i = -s_H$. We formalise these findings in Proposition 2 and summarise them in Table 3.4.

Proposition 2. *When $D + \delta \leq s_L$, in the Full Compliance equilibrium, the operator types pool on $p^* = s_H$, which is accepted by both manufacturer types. Waste is treated regardless of its quality.*

Full Compliance is the unique equilibrium if and only if ($\neg$ Bd) (i.e., (Bd) is not satisfied) and

$$s_H \geq c_I - \overline{v} + (1 - h)(s_L - \delta - D). \tag{FC}$$

Full Compliance is an equilibrium if and only if ($\neg$ Bd), ($\neg$ FC), and $s_H \geq \max\{c_I - \overline{v}, s_L - \delta\}$.

A necessary condition for the Full Compliance equilibrium is $s_H \geq c_I - \overline{v}$.

Condition (FC) is derived by ensuring that the expected profit of Operator I when charging $p^* = s_H$ and treating both types of waste ($E(\Pi_I) = p^* + \overline{v} - c_I$) is at least as much as the profit when charging $\tilde{p} = s_L - \delta$, which would only be accepted by Manufacturer L and be followed by dumping ($E(\Pi_I) = (1 - h)(\tilde{p} - D)$), i.e., $s_H + hv_H + (1-h)v_L - c_I \geq (1-h)(s_L - \delta - D)$. If condition (Bd) is satisfied, then the Breakdown equilibrium defeats a Full Compliance equilibrium. If neither (FC) nor (Bd) hold, there is a region where Full Compliance is an (undefeated, non-Pareto dominated) equilibrium, but is not unique as it coexists with Partial Compliance (discussed next).

The necessary condition states that the price ($p^* = s_H$) received by Operator I needs to be large enough to cover his expected cost of treating waste of expected quality $\overline{v}$. If this condition is not satisfied, the Full Compliance equilibrium cannot exist since Operator I would have a negative expected profit and deviate to a price that leads to a non-negative profit (e.g. setting a price so high that it is never accepted, leading to $\Pi_I = 0$). It is thus necessary that the price, i.e., the export cost of the high-quality waste, is sufficiently high for the Full Compliance equilibrium. The necessary condition for the Full Compliance equilibrium is illustrated in the dotted top triangle in Figure 3.2.
Comparing this equilibrium to the benchmark, we see that improving the information between waste chain partners can result in higher non-compliance rates. Specifically, with incomplete information, Operator I cannot selectively dump waste L. Thus, when the potential profit of treating high-quality waste exceeds the expected losses of treating low-quality waste for the same price, Operator I treats waste L, even though this would be suboptimal under complete information.

One drawback of the Full Compliance equilibrium is that to serve either manufacturer type, Operator E does not extract the full willingness to pay from Manufacturer

Table 3.4 Price and Profits in Full Compliance Equilibrium when $D + \delta \leq s_L$

Full Compliance			
	Waste Quality L	Waste Quality H	Price
Inefficient Facilities I	**Treat** $\pi_L = -p^*$ $\Pi_I = p^* + v_L - c_I$	**Treat** $\pi_H = -p^*$ $\Pi_I = p^* + v_H - c_I$	$p^* = s_H$
Efficient Facilities E	**Treat** $\pi_L = -p^*$ $\Pi_E = p^* + v_L - c_E$	**Treat** $\pi_H = -p^*$ $\Pi_E = p^* + v_H - c_E$	

Note. Each cell includes the following information about the equilibrium: (i) waste management outcome: Treat, Dump, or Export, (ii) the pooling price p^* offered by the treatment operator, (iii) the profit of the manufacturer π_i, and (iv) the profit of the operator Π_j. In contrast to the complete information benchmark, waste L is treated rather than dumped or exported.

L, whose outside option cost exceeds the charged treatment price ($s_L > p^* = s_H$). Manufacturer L therefore benefits from the low price meant for Manufacturer H and extracts more value than when under complete information, at the expense of the compliant efficient operator ($p_E^B = s_L > p^*$). One way to mitigate this damage, as we will see later on, is to increase s_H and reduce the difference between s_L and s_H.

The situation for Operator I is different, since in complete information his price was already limited due to a reduced willingness to pay for dumping. We find a range where Operator I is in fact better off in Full Compliance than in the benchmark, i.e., the profit of dumping L in complete information is less than the profit of treating L in incomplete information: $\Pi_I^B = (1-h)(s_L - \delta - D) < E\Pi_I^{FC} = (1-h)(s_H + v_L - c_I)$. To achieve this, it must be that $p^*(= s_H)$ is sufficiently higher than $p_I^B(= s_L - \delta)$. In all other cases, Operator I is worse off relative to the benchmark.

From a policy perspective, this can be considered as the most attractive outcome. However, the conditions for the Full Compliance equilibrium to emerge require that s_H, i.e., the export cost of high-quality waste, is sufficiently large. Although bans and restrictions on low-quality, hazardous waste are common, especially in Europe, export regulations on high-quality waste are limited. This suggests that the Full Compliance equilibrium would not be likely to emerge under the current regulatory climate, which is consistent with observations.

Partial Compliance Equilibrium: In this equilibrium, treatment survives for Operator type E, but high-quality waste is exported if paired with Operator I (Table 3.5). Adverse selection and moral hazard occur when the Operator is type I: Operator

I sets a price p_I^* that is only accepted by Manufacturer L (and for which Manufacturer H prefers to export), which reveals the low-quality nature of the waste. This waste is subsequently dumped by Operator I per Assumption 1. In contrast, Operator E treats both wast types by setting $p_E^* = s_H$. Due to the different pricing strategies of the operator types, Manufacturer L will be aware of the operator's type and intention to dump, adjusting her maximum willingness to pay accordingly. Therefore, Operator I charges $p_I^* \leq s_L - \delta$. We formalise these findings in Proposition 3 and summarise them in Table 3.5.

Table 3.5 Prices and Profits in Partial Compliance Equilibrium when $D + \delta \leq s_L$

Partial Compliance			
	Waste Quality L	Waste Quality H	Price
Inefficient Facilities I	**Dump** $\pi_L = -p_I^* - \delta$ $\Pi_I = p_I^* - D$	**Export** $\pi_H = -s_H$ $\Pi_I = 0$	$p_I^* \leq s_L - \delta$
Efficient Facilities E	**Treat** $\pi_L = -p_E^*$ $\Pi_E = p_E^* + v_L - c_E$	**Treat** $\pi_H = -p_E^*$ $\Pi_E = p_E^* + v_H - c_E$	$p_E^* = s_H$

Note. Each cell includes the following information about the equilibrium: (i) waste management outcome: Treat, Dump, or Export, (ii) the price p_j^* offered by the treatment operator, (iii) the profit of the manufacturer π_i, and (iv) the profit of the operator Π_j. In contrast to the complete information benchmark, waste H is exported if matched with Operator I rather than treated.

Proposition 3. *Under $D + \delta \leq s_L$, in the Partial Compliance equilibrium, Operator I sets $p_I^* \leq s_L - \delta$. Only Manufacturer L contracts with I, who dumps the waste. Operator E sets $p_E^* = s_H$, and gets and treats both types of waste.*

Partial Compliance (with $p_I^* = s_L - \delta$) is the unique equilibrium if and only if $(\neg FC)$, $(\neg Bd)$, and $s_H < s_L - \delta$.

Partial Compliance is an equilibrium if and only if $(\neg FC)$, $(\neg Bd)$, and $s_H \geq s_L - \delta$. It coexists with the Full Compliance equilibrium when $s_H \geq c_I - \overline{v}$ and with other Partial Compliance equilibria satisfying $p_I^* \leq s_L - \delta$ otherwise.

A necessary condition for the Partial Compliance equilibrium is:

$$s_H < \begin{cases} c_I - \overline{v} + (1-h)s_L & \text{when } c_E - v_L < 0 \quad \text{and } c_I - \overline{v} < 0 \\ c_I - hv_H + (1-h)(s_L - c_E) & \text{when } 0 < c_E - v_L \quad \text{and } c_I - \overline{v} < c_E - v_L \\ h(c_I - \overline{v}) + (1-h)s_L & \text{when } 0 < c_I - \overline{v} \quad \text{and } c_E - v_L < c_I - \overline{v} \end{cases} .$$

To understand the conditions of Proposition 3, we refer to the derivation of (Bd) in Proposition 1 to show that condition ($\neg$ Bd) is the opposite and must be satisfied or Breakdown would exist and defeat Partial Compliance. Condition ($\neg$ FC) is the opposite of (FC) in Proposition 2 and must be satisfied or Full Compliance would exist and defeat Partial Compliance. If neither (FC) nor (Bd) hold, there is a region where Partial Compliance is an equilibrium, but is not unique as it coexists with the Full Compliance equilibrium.

The necessary condition is derived by writing ($\neg$ FC) in terms of international enforcement efforts that corresponds to setting $\delta = 0$ and $D = \max(0, c_E - v_L, c_I - \overline{v})$ (driven by Assumption 1), which are the values for which the domestic enforcement efforts D and δ are at their minimum. The necessary condition for the Partial Compliance equilibrium is illustrated in the horizontally striped region in Figure 3.2.

Since the operator's type is signaled in this equilibrium, Operator I is no longer able to benefit from information asymmetry as he did in the Breakdown equilibrium. As such, Operator I earns the same by dumping the low-quality waste as in the complete information benchmark, but misses out on the high-end market and therefore has strictly lower expected profits than in the benchmark case. Manufacturer L, however, can benefit from the low price meant for Manufacturer H as she did in Full Compliance at the expense of the efficient operator.

From a policy perspective, this equilibrium is an intermediate outcome since the efficient operator fully complies, but the inefficient operator dumps, resulting in export of high-quality waste.

Stronger domestic enforcement

This subsection explores the effect of stronger domestic anti-dumping enforcement ($D+\delta > s_L$). This scenario is more in line with the current state of the European Union, which has tough enforcement of domestic violations of e-waste laws. Recall that in the complete information benchmark, this move resulted in a shift from dumping to export, which we referred to as the "displacement effect". Under incomplete information, we find two major tipping points where the displacement occurs. In the Partial Compliance equilibrium, dumping is eliminated in favor of exporting when $D + \delta > s_L$. In the Breakdown equilibrium, stronger domestic enforcement is needed to curb dumping, namely $D + (1 - \gamma)\delta \geq s_L$. The reason is that moral hazard under incomplete information allows Operator I to pool on the price which makes him indistinguishable from the other operator type who does not dump. As a result, dumping is more resilient against domestic enforcement efforts in the Breakdown equilibrium than in the Partial Compliance equilibrium where the prices signal the type of the operator. We provide the exact necessary and sufficient conditions for the equilibria under stronger domestic enforcement in Propositions 4 and 5 in the Appendix, and highlight the displacement conditions in Lemma 2.

Lemma 2. *Under incomplete information, dumping of waste L by Operator I is replaced by export for* $D + \delta > s_L$ *in the Partial Compliance equilibrium, and for* $D + (1-\gamma)\delta \geq s_L$ *in the Breakdown equilibrium.*

Table 3.6 summarises all equilibrium necessary and sufficient conditions. Figure 3.3 shows these conditions in terms of domestic policy enforcement efforts (D, δ) for two export policy climates (s_L, s_H) represented by points B and C in Figure 3.2. Examining Table 3.6, we find two main implications of enforcement efforts under information asymmetry beyond the displacement effect.

Table 3.6 Summary Equilibrium Necessary and Sufficient Conditions

Equilibrium	$D \leq s_L - \delta$	$s_L - \delta < D < s_L - (1-\gamma)\delta$
Breakdown	(Bd)	(Bd)
Full Compliance	$(\neg\,\text{Bd})$ *and* (FC) *or* $(\neg\,\text{Bd})$ *and* $s_H \geq \max\{c_I - \overline{v}, s_L - \delta\}$	$(\neg\,\text{Bd})$ *and* $s_H \geq c_I - \overline{v}$
Partial Compliance	$(\neg\,\text{Bd})$ *and* $(\neg\,\text{FC})$	$(\neg\,\text{Bd})$ *and* $s_H < c_I - \overline{v}$

Equilibrium	$D \geq s_L - (1-\gamma)\delta$
Breakdown	(Bd-s)
Full Compliance	$s_H \geq c_I - \overline{v}$ *and* $(\neg\,\text{Bd-s})$
Partial Compliance	$s_H < c_I - \overline{v}$

Note: (FC) $\equiv s_H \geq c_I - \overline{v} + (1-h)(s_L - \delta - D)$, (Bd) $\equiv s_H \leq h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta)$, and (Bd-s)$\equiv s_H < h(c_E - v_H) + (1-h)\min\{D, s_L\}$ (see Proposition 5)

First, under sufficiently strong domestic enforcement $(D + (1-\gamma)\delta > s_L)$, the efficient operator can achieve higher profits in the Breakdown equilibrium than in Partial Compliance for high levels of D. The driver is that high levels of D remove the threat of Operator I pooling on the price (as he does in Breakdown under weak domestic enforcement) due to high dumping cost. As D increases, the efficient operator can charge a higher price in Breakdown without risking Operator I entering the market, pooling on the price, and dumping the waste. Thus, Breakdown becomes more attractive relative to Partial Compliance for Operator E. This means that strong domestic enforcement levels may discourage non-compliant operators from participating in the market, but they may also encourage unwanted behaviour by operators initially in compliance (the efficient operator sets a price that is too high for the high-quality waste manufacturer who then exports.).

Second, the condition for which Full Compliance becomes the unique equilibrium is less stringent under stronger domestic enforcement than under weak domestic enforcement. The driver behind this finding is that Operator I incurs a loss if he were to dump in Partial Compliance under strong domestic enforcement efforts ($D + \delta > s_L$) and in Breakdown under even stronger enforcement efforts ($D + (1 - \gamma)\delta > s_L$). To avoid this loss, he can price himself out of the market by setting p_I^* sufficiently high and earn a zero profit (a manufacturer of either type will export rather than contract with that operator). As long as treating both waste types is profitable ($E\Pi_I \geq 0$), Full Compliance defeats Partial Compliance and Breakdown (whereas under weak enforcement, treating both wastes needed to be more profitable than dumping for this to happen).
In the next section, we evaluate the policy implications of these results and rely on a combination of Figures 3.2 and 3.3 to convey the intuition.

3.5 Policy implications

3.5.1 Export restrictions

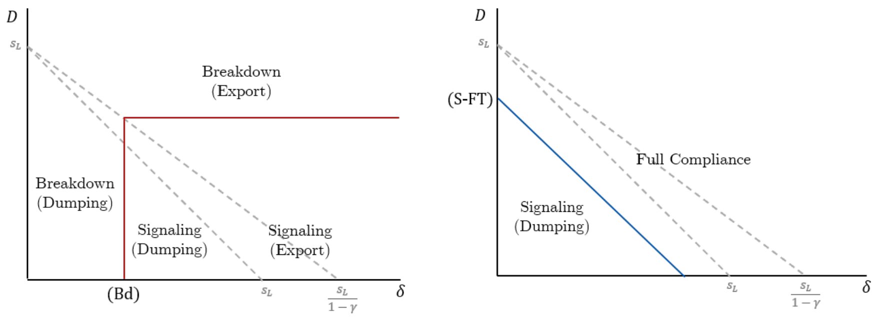
This section evaluates the effect of changes in the level of internationally orientated regulations and enforcement and in particular which waste categories they target. For instance, in 2017 the enforcement of the Waste Shipment Regulations was strengthened. This would raise the export cost of hazardous waste s_L but would barely affect s_H. Similarly, in December 2019, the Basel Ban Amendment became international law and violators who export low-quality waste will be charged as such, significantly increasing the expected cost of exporting illegally (s_L).

Export restrictions are important for the domestic market as they influence how well local operators can compete with the outside market. We show that when firms have incomplete information on their supply chain partner, the difference in export burden between waste categories is crucial in determining equilibrium outcomes. We will illustrate this finding using Figure 3.2 where an increase in the stringency of export regulations on low-quality waste (s_L) represents a move from point A, where

Fig. 3.3 Equilibrium Outcome as a Function of the Domestic Policy Climate

(a) Breakdown and Partial Compliance (b) Partial and Full Compliance

Equilibria in point B of Figure 3.2 Equilibria in point C of Figure 3.2



Note. The heavy solid lines illustrate the necessary and sufficient conditions that partition the domestic enforcement space into regions corresponding to different waste management equilibria in the (D, δ) space for a fixed (s_L, s_H) pair. The two dotted lines represent the two tipping conditions from dumping to export identified in Lemma 2. They are solid in the equilibrium regions where they are operational and the parenthetical specification of Dumping and Export marks their effect. Figures 3.3a and 3.3b show examples where s_L and s_H satisfy the conditions of Partial Compliance and Breakdown, and of Partial and Full Compliance, respectively. Figure 3.3a illustrates the finding that under sufficiently strong domestic enforcement, increasing D may result in a move from Partial Compliance to Breakdown. Figure 3.3b illustrates the finding that the condition for which Full Compliance becomes the unique equilibrium is less stringent under stronger domestic enforcement than under weak domestic enforcement.

only Partial Compliance exists, to B, where the necessary conditions of both Partial Compliance and Breakdown are satisfied.

Strengthening export regulations on low-quality waste means that the export market becomes less attractive for Manufacturer L. Operator I, who only contracted with Manufacturer L in point A, can respond to a move to point B by increasing his price for Manufacturer L without risking that she resorts to export. Operator E, who contracted with both manufacturer types in point A, cannot raise his price without Manufacturer H switching to export as the cost of export for Manufacturer H, s_H, remains unchanged. If the opportunity cost of keeping Manufacturer H's business becomes too high, Operator E will also induce adverse selection, resulting in the Breakdown equilibrium. We can see this in Figure 3.3a, corresponding to point B in Figure 3.2, where the Breakdown region expands with s_L (i.e., the (Bd) line shifts to the right).

This simple example illustrates the danger of export regulations that only focus on avoiding the export of low-quality waste. This is one of the most revealing results of our paper. To restate the example above in more general terms, when export regulations increase the maximum price an operator can charge the low-end market, at some point, serving only the low-end market becomes more attractive than serving the full market (under incomplete information). Consequently, the high-quality waste market is exported rather than treated domestically and thus no longer functions well due to these regulations.

To avoid this unintended outcome of export restrictions, the opportunity cost of forgoing the high-quality market would need to be increased. This can be attained through two mechanisms. First, the operator must be able to charge a sufficiently high price to make treating the whole market profitable without risking that Manufacturer H resorts to export. This can only be achieved if the export costs of both waste types (s_H and s_L) are sufficiently high. This effect is illustrated by moving from point A to point C in Figure 3.2 where the necessary condition for the Full Compliance equilibrium is satisfied. Second, the sufficient conditions of the Full Compliance equilibrium (i.e., (¬Bd) and (FC)) require that the difference in the price that the operator can charge the two manufacturer types is sufficiently small. In other words, we need more symmetric export regulations between waste categories to ensure that the costs s_L and s_H do not drift too far apart. These interventions can facilitate the move from Partial Compliance or Breakdown to Full Compliance, where all waste is treated regardless of the quality or the efficiency of treatment facilities. We state these results more formally in Corollary 1.

Corollary 1. *Starting from the Partial Compliance equilibrium, more stringent export regulation on waste L can lead to the Breakdown equilibrium where Manufacturer H exports. Combining this measure with appropriately tailored export regulations on waste H discourages adverse selection and can lead to the Full Compliance equilibrium where either waste type is treated.*

Existing literature on environmental economics has argued the importance of reducing regulatory differences between countries to reduce the trans-boundary movement of waste. These studies focus on the effect of regulatory changes on the compliance of a single firm, whereas in reality, waste chains consist of multiple agents. Our contribution to this literature is to model interactions between two key agents in a decentralised waste chain, which reveals a new dimension: the necessity of reducing regulatory differences between waste categories.

Although the benefit of the Full Compliance equilibrium is clear from a waste management outcome perspective, we also wish to understand its effect on profits which drive stakeholder support. Specifically, we find that the benefits of an increase in s_H are not captured as easily by Operator I as by Operator E. For instance, if the starting point is the Breakdown equilibrium, an increase in s_H encourages Operator E to signal his efficiency and contract with either manufacturer type by charging $p_E^* = s_H$. In the resulting Partial Compliance equilibrium, Operator E benefits from an increase in s_H through the price, but Operator I has lower profits than in Breakdown since he cannot hide his dumping activities anymore ($p^* < p_I^*$ in Table 3.3 and 3.5). Operator I will only benefit from increases in s_H once the conditions for Full Compliance are satisfied, in which case he can credibly signal that he will treat, eliminating the reduced willingness to pay that comes with dumping. Crucially, his profits may even exceed those he received under complete information ($\Pi_I^B < E\Pi_I$ for waste L in Tables 3.2 and 3.4).

This insight is important for the broader implications of this study by foreshadowing potential industry push-back against the implementation of these bans. Clearly, the efficient operator should always support export regulations that apply to a broader range of waste categories, but both operator types will only fully benefit once Full Compliance is the equilibrium. Thus, even if the inefficient operator is negatively affected at first, export regulations will increase his profits if those regulations are sufficiently strong to satisfy the sufficient conditions of the Full Compliance equilibrium. In other words, incentives of the two operator types are aligned with those of authorities when the export regulations on high-quality waste are sufficiently stringent.

As we described above, export regulations can ensure the necessary conditions for the Full Compliance equilibrium are met, but these regulations may need to be complemented with local anti-dumping enforcement efforts to ensure the sufficient conditions are met.[8] For instance, in point C of Figure 3.2, the necessary condition of Full Compliance is satisfied, but also that of Partial Compliance, which means that export regulations alone are not enough to determine which of the two will be the equilibrium: Domestic anti-dumping enforcement to complement export regulations may be necessary, which is discussed next.

[8]The upper left region of Figure 3.2 is the exception to this. Being in this region requires imposing as strict bans on high-quality waste as those on hazardous waste, which is often a politically unfeasible strategy.

3.5.2 Domestic anti-dumping enforcement

In this section, we evaluate the effect of a change in the strength of domestic enforcement against dumping, and in particular the relative cost incurred by the manufacturer (through δ) versus the operator (through D). Under complete information, we know that it is the aggregate dumping cost $D + \delta$ that solely determines the equilibrium outcome: When the magnitude of $D + \delta$ exceeds s_L, waste L is exported rather than dumped (displacement effect). In this section, we will show that when firms have incomplete information about their supply chain partner, not just the aggregate dumping penalty but also the relative penalty incurred by the operator versus the manufacturer, D and δ, respectively, can be crucial in determining the equilibrium outcome. Consequently, the level of the waste supply chain that is targeted by anti-dumping policies matters. We will illustrate these findings with Figures 3.3a and 3.3b (which correspond to points B and C in Figure 3.2), using either the Partial Compliance equilibrium or the Breakdown equilibrium as the starting point, and formalise them in Corollaries 2 and 3.

Strengthening domestic enforcement efforts can be highly effective and lead to the treatment of both waste types when the cost of exporting high-quality waste (s_H) is relatively high ($c_I - \overline{v} < s_H < s_L$). This can be illustrated in Figure 3.3b where, starting under the conditions of the Partial Compliance equilibrium (where the market functions well for Operator E, who treats both waste categories, but fails when waste reaches Operator I), an increase in either D or δ can satisfy the necessary and sufficient conditions of Full Compliance (where waste is treated by both operator types). Since this result may not hold when s_H is not sufficiently high, this example illustrates the complementarity of domestic enforcement efforts and export regulations.

However, there is a nuance to this solution: Strengthening domestic anti-dumping enforcement by targeting the treatment operator (increasing D) can backfire and cause the high-quality manufacturer to export her waste regardless of the operator with whom she is matched. This can occur when the cost of exporting high-quality waste (s_H) is sufficiently low. To illustrate this, consider that export costs correspond to point B in Figure 3.2 and the Partial Compliance regime in Figure 3.3a is in effect. Here, an increase in D (vertical shift) can lead to the Breakdown equilibrium. To explain why, recall that in §3.4.2 (or Proposition 5), we found that entering into a contract with manufacturer L is not profitable for Operator I under strong domestic anti-dumping enforcement. As Operator I prices himself out of the market, the problem of moral hazard under incomplete information, which undermines the profit of Operator E in

Breakdown, is eliminated. However, the threat of being undermined by Operator I may have been what kept the efficient operator from inducing adverse selection and avoiding the Breakdown equilibrium. Now that stronger anti-dumping enforcement has discouraged Operator I from participating in the market, Operator E has a greater incentive to raise his price and select on low-quality waste, causing waste H to be fully exported, resulting in the Breakdown equilibrium. Thus, a market that functions relatively well (Operator E treats both waste categories) can be negatively affected if ill-placed enforcement efforts remove the threat of moral hazard, further increasing the export of valuable waste (Operator E only treats low-quality waste). We formalise these findings in the following corollary.

Corollary 2. *Starting from the Partial Compliance equilibrium, stronger domestic enforcement efforts*

i. can lead to Full Compliance as the equilibrium through an increase in $D + \delta$ when the profile of export regulations is such that the necessary condition holds (Proposition 2).

ii. can backfire and lead to Breakdown as the equilibrium through an increase in D if this change satisfies Proposition 5(iii).

We now turn to analyzing the effect of targeting the manufacturer with anti-dumping regulation (increasing δ). We already noted this can improve waste management outcomes under some conditions (item i. of Corollary 2). We identify another such set of conditions by considering the necessary and sufficient conditions of the Breakdown equilibrium in Figure 3.3a, at export costs associated with point B in Figure 3.2. Recall that under Breakdown, all high-quality waste is exported. Exacerbating the consequences of dumping for the manufacturer by increasing δ can lead to the Partial Compliance equilibrium where the high-quality waste is treated by the efficient operator. What happens is that the manufacturer's willingness to pay if the operator will dump is reduced. Consequently, the (pooling) price that the efficient operator will obtain is diminished and he is encouraged to signal his type by treating the complete market. Although not illustrated in this figure, an increase in δ can also lead to Full Compliance, provided the necessary conditions hold. In contrast, an increase in the dumping cost D incurred by the treatment operator (vertical shift in the figure within the Breakdown region) does not improve the waste management outcome other than displacing waste L between dumping and export.

There is a nuance to consider when strengthening anti-dumping efforts that target the manufacturer, too: The profit of the efficient operator might be undermined. Referring again to Figure 3.3a, if an increase in δ is too small such that condition (Bd) still holds, dumping will continue to occur while the operator's type cannot be distinguished by the manufacturer. With an increase in δ, the manufacturer is subject to stronger domestic enforcement and her willingness to pay for waste management services is reduced further. As such, the market price $p^* = s_L - (1-\gamma)\delta$ falls and the efficient operator is negatively affected. We formalise these findings in the following corollary.

Corollary 3. *Starting from the Breakdown equilibrium, stronger domestic enforcement efforts*

i. can lead to Partial Compliance as the equilibrium through a sufficient increase in δ if the change satisfies Proposition 3 or 4(ii).

ii. can lead to Full Compliance as the equilibrium through a sufficient increase in δ if the change satisfies Proposition 2 or 4(i).

iii. can backfire and lead to a lower profit for Operator E through an insufficient increase in δ if the change does not satisfy any of the above conditions.

Combining the above corollaries, we conclude that targeting the manufacturer (increasing δ) is a more robust anti-dumping measure as it always (weakly) improves the waste management outcome, while targeting the treatment operator is a policy approach that should be implemented more judiciously. In particular, it is effective when combined with a sufficiently high export cost but can lead to a worse waste management outcome otherwise.

In current waste management implementations, producer cost for downstream violations is a relatively nascent practice. Yet, since it is necessary to set minimum operating requirements for extended producer responsibility schemes, we recommend that targeting manufacturer cost would be an effective requirement. When this measure cannot be implemented, Full Compliance can still be attained by introducing more symmetric export regulations between waste categories (Corollary 1) and strengthening domestic anti-dumping enforcement by targeting the treatment operator (Corollary 2), though there is a risk that the latter backfires if the export cost of high-quality waste is insufficiently high.

In the environmental economics literature, the dumping cost for the manufacturer and operator are rarely separated as the studies either incorporate only one of those agents (e.g. Ino (2011), or only consider the cost for which an agent is directly responsible, such as emissions for manufacturers or disposal for operators (e.g. Walls et al. (2001)). By capturing the cost (e.g. fines, reputation loss) for the manufacturer from dumping, we find that the compliance and waste management outcomes depend on who is targeted with anti-dumping regulations and under what conditions.

3.5.3 Summary Findings regarding Export and Anti-Dumping Policies

We briefly summarise our main findings from this section:

1. Strengthening export regulations on high-quality waste to make export regulations more symmetric increases the opportunity cost of forgoing the high-quality market and can lead to waste being treated regardless of the quality or the efficiency of treatment facilities (Corollary 1). This improves the profit of the efficient operator as he signals his type by treating the complete market, but will only improve the profits of the inefficient operator once Full Compliance is achieved.

2. An increase in the dumping cost for the manufacturer is an effective, complementary measure to export regulations on high-quality waste as it reduces the manufacturer's willingness to pay when dumping activities occur (Corollaries 2.i, 3.i, and 3.ii).

3. If domestic enforcement efforts are not designed in conjunction with export regulations, they can end up undermining profits of the efficient operator or even worsening waste management outcomes (Corollaries 2.ii and 3.iii).

3.6 Robustness of Results

We relax two key assumptions and explore their implications for our findings and recommendations outlined in §3.5.3. The model development and proofs can be found in Appendix C.

3.6.1 Quality Verification by the Treatment Operator

Our model assumes that the treatment operator cannot ascertain the quality of waste without going through the treatment process. Instruments that sort products by recyclability or other characteristics have been shown to be inefficient and costly to implement (European Commission, 2014). Our current assumption is based on these observations. We recognise, however, that as technology progresses, there may be cases where a treatment operator can perform a (costly) assessment of the quality of the waste after having obtained it but before processing it. We therefore extend the model to allow the operator to perform a quality check of cost T that perfectly reveals waste quality prior to deciding his disposal method, conditional on the manufacturer contracting him for his waste management services. Assumptions 1 and 2 and the benchmark analysis remain unchanged since there is no information asymmetry with respect to the waste quality.

In the decentralised waste management chain, the efficient operator does not have an incentive to perform a quality check as his strategy is to treat any waste he is contracted to manage regardless of its quality (by Assumption 1(i)). The inefficient operator, on the other hand, is willing to incur this cost if the loss of unknowingly treating low-quality waste due to incomplete information is high relative to the cost of verification and dumping the waste if it is of low quality, i.e., $(1-h)(c_I - v_L) > T + (1-h)D$. Our original model can be interpreted as T being sufficiently high such that there is never an incentive to verify waste quality. In contrast, we find that when T is low enough for the above condition to hold, the inefficient operator performs a quality assessment when either waste manufacturer would accept his price, causing the Full Compliance equilibrium to disappear. Instead, a new pooling equilibrium emerges with $p^* = \min\{s_H, s_L - (1-\gamma)\delta\}$, where the efficient operator treats without quality verification, and the inefficient operator verifies quality, dumps if the check reveals the waste is of low quality, and treats otherwise. We will refer to this as the Near-Full Compliance equilibrium, with $p^* = \min\{s_H, s_L - (1-\gamma)\delta\}$.

A low-cost quality assessment has several implications for our findings in §3.5.3. First, strengthening export regulations on high-quality waste continues to be beneficial as it can lead to the Near-Full Compliance equilibrium where all high-quality waste is treated as in Corollary 1, a strict improvement compared to Partial Compliance and Breakdown. In addition, the threshold export cost on high-quality waste where this improvement can be attained is lower than the threshold for Full Compliance, i.e., the new pooling equilibrium can emerge under more asymmetric export regulation profiles of the two waste types. Moreover, strengthening export regulations on high-quality waste can still improve the profits of both operator types. However, there exists a limit. As a result of the pooling price, the low-quality manufacturer cannot know a priori if her waste is dumped, lowering her willingness to pay. As a result, moral hazard impacts willingness to pay when s_H exceeds $s_L - (1-\gamma)\delta$ (such that $p^* = s_L - (1-\gamma)\delta$), and the profits of the efficient operator are negatively affected due to the dumping activities being hidden. This mechanism is similar to the issue of moral hazard under incomplete information in the Breakdown equilibrium (Proposition 1) of the original model, except that high-quality waste is still treated.

The way in which domestic anti-dumping enforcement efforts can complement export regulations is less straightforward than in Corollaries 2 and 3 because the inefficient operator dumps in the Near-Full Compliance equilibrium, with two main implications. First, an increase in the dumping cost for the manufacturer continues to be an effective, complementary measure to export regulations on high-quality waste. One exception where this measure can be ineffective (the Near-Full Compliance equilibrium is not attained) is when the moral hazard condition holds ($s_L - (1-\gamma)\delta < s_H$). Therefore, in the presence of quality verification, we must take additional care that the export cost of high-quality waste (s_H) is tailored in conjunction with δ to avoid satisfying the moral hazard condition. Second, an increase in the cost of dumping for the operator can backfire. Rather than contracting with both manufacturer types and dumping only low-quality waste, the inefficient operator prefers to fully price himself out of the market. Thus, there still exists a backfiring condition as in Corollary 2.ii, but for a different reason.

In reality, the assessment cost T will lie somewhere in the middle of the two cases that we have described. This means that to ensure a Full Compliance scenario is possible, the penalty of violating anti-dumping regulations for treatment operators (D) must be sufficiently high to discourage inefficient operators from verifying the quality to identify and dump low-quality waste.

3.6.2 Quality Uncertainty

Our model also assumes that the manufacturer knows the quality of her own waste. In some cases, the agent contracting the treatment operator may not be the original generator of the waste. For instance, since the introduction of take-back regulations, manufacturers in Europe have created entities called Producer Responsibility Organizations. These PROs contract the treatment operator on behalf of their members and therefore correspond to the 'manufacturer' in our waste chain model. Although the organization is run by its member companies, when the waste originates from several sources, it can introduce quality uncertainty for the PRO.

To capture this, we adapt our model such that the manufacturer is uncertain about the quality of her waste, but has an informative signal about the most likely quality level. We define conditions paralleling Assumptions 1 and 2 such that the benchmark equilibrium outcome is as in Lemma 1 (the waste is treated except when the manufacturer with the lower expected waste quality works with an inefficient operator). We find that the equilibrium structure is robust with respect to quality uncertainty: In the decentralised case, the same three equilibrium outcomes (Breakdown, Full Compliance, and Partial Compliance) emerge. Referring back to the key findings in §3.5.3, reducing the asymmetry in export cost between waste categories remains important. Adverse selection is eliminated by ensuring that exporting high-quality waste is sufficiently costly, which increases the price operators can charge in the domestic market (Corollary 1). Strengthening domestic enforcement efforts continue to be a highly effective complement to export regulations and lead to the treatment of both waste types, provided they are carefully tailored in conjunction with export regulations to avoid them backfiring (Corollaries 2 and 3).

3.7 Concluding Remarks and Recommendations

This work was inspired by discussions with Europol officers who recognised the challenges of determining what enforcement actions to prioritise while operating under imperfect information. Our work aims to provide insights for policymakers and organizations using a model-based approach to analyse how the regulatory climate interacts with the organizations' profits and choice to comply. This is an especially promising approach for the analysis of illicit markets as data is rarely available due to the hidden nature of illegal activities (EnviCrimeNet, 2015).

Agencies note that illegally dumping or exporting hazardous materials like electronic waste, chemicals and industrial waste is "an easy alternative due to the cost of responsible waste disposal, differences in regulations and enforcement efforts between countries, and weak enforcement systems" (Interpol, 2019). We build on this notion and find additional factors that influence compliance and waste management outcomes, which leads us to the following conclusions.

The asymmetry in export burden between waste categories should be reduced: Existing single-agent studies have shown the importance of reducing regulatory differences between countries to avoid the pollution haven effect. We find that the pollution haven hypothesis gives an important but incomplete explanation of the violations we see in the market. Our results suggest that with multi-agent problems, we need to reduce the asymmetry in regulatory stringency (reflected in the export cost) between waste categories. This is because export regulations directly influence how well local treatment operators can compete with the outside market. The easier it is for manufacturers to export, the lower the price domestic operators can charge. When more low-quality waste stays in the local market because of high export cost, adverse selection pushes prices up, driving providers of high-quality waste abroad, while moral hazard under incomplete information makes illegal dumping more attractive, undermining profits of compliant treatment operators. In other words, regulations targeted at one market failure (the export of low-quality waste) can spill over to market segments that were functioning well (the local treatment of high-quality waste). Regulations must be well-balanced and consider how the market functions as a whole rather than isolating single agents.

Consider the Basel Ban Amendment that became international law in December 2019. This law bans the trans-boundary movement of hazardous waste but does not apply to higher quality waste. Although this measure would attain its goal under complete information, it can backfire and create perverse incentives in a waste chain with information asymmetry as described above. Considering Europe, if this ban on amber-listed waste is combined with regulations that also increase the cost of exporting green-listed waste, the price operators can charge in the domestic market increases and it becomes more profitable for operators to attract high-quality waste. Ultimately, this can lead to treatment of all wastes types even by operators who were initially in non-compliance, ensuring valuable resources are retained and extracted efficiently in the local market.

Treatment operators should consider supporting balanced export regulation: From the perspective of the operators, we find that efficient operators will reap the benefits of costlier export for high-quality waste more easily than inefficient operators, and the improvement in the profits of efficient operators will initially come at the expense of inefficient operators as these measures can reveal them as being inefficient. However, once export regulations on high-quality waste are sufficiently strong, inefficient operators also benefit from balanced export regulation.

Penalizing manufacturers for downstream dumping should be given more consideration: We find that domestic anti-dumping enforcement that affects the dumping cost for manufacturers and treatment operators can complement the export measures in achieving full compliance. Increasing the cost of dumping on treatment operators can eliminate moral hazard and encourage treatment, but may also cause a displacement effect upstream, causing formerly dumped waste to be illegally exported instead. Increasing the dumping cost borne by manufacturers instead can be particularly effective because it penalises non-compliant operators through a reduction in willingness to pay for services. This finding supports the relatively nascent EPR practice of holding the manufacturer responsible for downstream violations.

Domestic anti-dumping enforcement efforts must be carefully crafted in conjunction with export regulations so they do not backfire: If the cost of exporting high-quality waste is sufficiently low, increasing the dumping cost on the treatment operator too much may increase the export of valuable waste, while increasing the dumping cost on the manufacturer too little will undermine the profits of compliant treatment operators without changing waste outcomes. Thus, the export regulation and domestic enforcement levers should be designed to work effectively in concert.

Policies or incentives that support quality verification should be coupled with strengthened anti-dumping regulation: Governments can pursue measures to reduce the cost of quality verification by treatment operators, including information-based approaches or technology subsidies. We find that adverse selection is less likely to occur, and high-quality waste is more easily retained and treated in the country of origin, when it can be more easily identified. The main disadvantage is that operators can also use this information to identify low-quality waste and dump it. This incentive can create additional moral hazard problems, further undermining the profit of compliant operators. Strengthening and tailoring penalties for dumping in conjunction with export regulations will help forestall this outcome.

Discussion of Limitations and Future Research. We considered treatment as the best possible waste management outcome, and dumping and export as outcomes to avoid. The problem of export is, however, more nuanced. One could argue that in many developing countries people now depend on waste from the global north as secondhand markets have been established, and that the export of high-quality waste created through adverse selection is not a real problem. Some counterarguments are that valuable components are often extracted under dire and life-threatening conditions, that residual wastes create environmental pollution, and that globally we are losing out on a significant amount of resources as extraction practices in developing countries are much more inefficient. In addition, our results show that when high-quality waste leaves the domestic market, the low-quality nature of the remaining waste is revealed, increasing the incentive for local, inefficient operators to dump. This finding strengthens the case for considering any waste export to be undesirable.

We focused on two-sided information asymmetry because this is the prevalent condition in waste markets. One may ask how the above policy recommendations affect waste outcomes in a specific dyad where one-sided information prevails, and in particular, waste quality is known by the operator prior to setting his price. In this case, the operator can perfectly discriminate his price based on quality, and the equilibrium outcome is the same as in the benchmark case with one important distinction: treatment operators pool on price for the low-quality waste. We find that the only impact of the policy climate on waste outcomes in this case is whether waste is exported versus dumped (displacement effect); treatment is not affected. However, we note that the operator can only know the waste quality from a given manufacturer with certainty if product designs and manufacturing processes remain unchanged, PRO memberships and their waste streams are stable, and the waste recovery value does not change over time. These conditions are highly specific and do not apply to the majority of waste chain relationships. The converse is even less likely: Learning about the operator type even in ongoing relationships is challenging because legal business structures are often used for illicit activities (Europol, 2017), prominent companies with valid certifications commit violations (Geeraerts et al., 2015), and the only way to uncover a non-compliant operator is not before or after dumping, but only when he is caught dumping. Yet, even this information often disappears quickly (e.g. Churngold recycling from the introduction changed its name to South West Recycling after the dumping scandal).

The waste and operator characteristics are modeled as exogenous parameters as they depend on previous product design and facility technology investments. If these characteristics change (via manufacturer product and process redesign or operator investment in treatment technology), the market characteristics and the agents' expectation about their channel partner would change accordingly. Although this may influence waste outcomes, our policy recommendations which focus on improving those outcomes continue to hold. Targeted incentives for manufacturers to improve post-use recovery value or for operators to invest in treatment technology could however complement our recommendations. For instance, a greater expected waste quality in the market lets waste treatment emerge as a preferred strategy under more asymmetric export regulations. Thus, a promising future research area on this topic is the investigation of product design and technology investment incentives to uncover this potential complementarity.

We assumed a non-competitive market structure for waste treatment (a single operator whose efficiency is unknown by the manufacturer) to obtain fundamental insights about the implications of information asymmetry. The direct applicability of this assumption depends on the waste category. Competition between treatment operators in markets for waste oil is limited (due to the specialised facilities needed), but the market for e-waste has become more competitive (European Commission, 2014). A future research direction is to consider a competitive market model where the efficient and inefficient operator can cater to the same manufacturer.

As a final note, we know that as long as the current conditions continue and waste production increases with the population, the problem of illicit waste management will only continue to grow and undermine not only honest competitors, but also have a devastating impact on our environment and public health. We hope our research can contribute to the decision making of enforcement agencies and firms active in waste disposal by shedding light on possible unwanted effects of policy measures on compliant firms and by identifying how to use policy most effectively to encourage proper waste management.

3.8 Appendix

3.8.1 Complete Information

Proof of Lemma 1: We solve the game depicted in Figure 1 under complete information using backward induction starting in period 3.

Period 3: If Operator j treats the waste, his profit will be $\Pi_j(T) = p_j + v_i - c_j$. If he dumps it, his profit will be $\Pi_j(P) = p_j - D$. Hence Operator j treats waste i iff $\Pi_j(T) \geq \Pi_j(P)$ i.e., iff $D \geq c_j - v_i$; he dumps it otherwise. Thus when solving period 2, we need to look at two different cases if Operator j gets the waste in period 3: (i) he treats or (ii) he dumps.

(i) Case $(i, j) \in \{(H, E), (H, I), (L, E)\}$: The operator treats the waste since $D \geq c_E - v_L$, $D \geq c_I - v_H$ and $D \geq c_E - v_H$ by Assumptions 1(i) and (iii).

Period 2: If Manufacturer i accepts the offer of Operator j, her waste will be treated and thus her cost will be p_j. If she rejects and exports her waste, her cost will be s_i. Hence Manufacturer i minimises her cost by accepting Operator j's price iff $p_j \leq s_i$.

Period 1: If Treatment Operator j sets $p_j \leq s_i$, Manufacturer i will accept and he will treat her waste, leading to $\Pi_j(T) = p_j + v_i - c_j$. If he sets $p_j > s_i$, the waste will be exported and $\Pi_j(X) = 0$. Operator j sets the price that maximises his profit. Thus, when $s_i < c_j - v_i$, the Treatment Operator charges a price that will not be accepted, $p_j^* > s_i$. But when $s_i \geq c_j - v_i$, he charges the maximum fee to Manufacturer i that she will accept, $p_j^* = s_i$. Under Assumption 2, $s_i \geq c_j - v_i$ holds for $(i, j) \in \{(H, E), (H, I), (L, E)\}$. Therefore, both operators set $p_j^* = s_H$ when waste quality is H and Operator E sets $p_E^* = s_L$ when waste quality is L.

(ii) Case $(i, j) = (L, I)$: The operator dumps the waste since $D < c_I - v_L$ by Assumption 1(ii).

Period 2: If Manufacturer L accepts the offer of Operator I, her waste will be dumped and thus her cost will be $p_I + \delta$. If she rejects and exports her waste, her cost will be s_L. Hence Manufacturer L accepts iff $p_I \leq s_L - \delta$.

Period 1: If Treatment Operator I sets $p_I \leq s_L - \delta$, Manufacturer L will accept and he will dump her waste, leading to $\Pi_I(P) = p_I - D$. If he sets $p_I > s_L - \delta$, the waste will be exported and $\Pi_I(X) = 0$. Thus, for $D \leq s_L - \delta$, he charges the maximum fee to Manufacturer L that she will accept, $p_I^* = s_L - \delta$. For $D > s_L - \delta$ the Treatment Operator charges a price that will not be accepted, $p_I^* > s_L - \delta$.

3.8.2 Incomplete Information

We solve the game under incomplete information using backward induction starting in period 3. When multiplicity arises, we select the Pareto efficient one, if such an equilibrium exists, and apply the undefeated equilibrium refinement by Mailath et al. (1993). The refinement requires beliefs about out-of-equilibrium actions to be valid only if those actions correspond to an alternative equilibrium. This refinement is appropriate for our setting with double-sided information asymmetry and a receiver (in addition to the sender) that can be of different types. For the interested reader, we refer to Bajaj (2018); Wang (2020). We use the following definition, adapted from Mailath et al. (1993):

Definition 1 (Undefeated Equilibrium). *Equilibrium σ' is defeated if it coexists with another equilibrium σ and there exists a price p such that:*
(D1.1) price p is off-equilibrium for σ' ($\forall j \in \{E, I\}$ $p'_j \neq p$) but on the equilibrium path of σ and chosen by operator type(s) in $K = \left\{j \in \{E, I\} | p_j = p\right\}$ (i.e., $K \neq \varnothing$).
(D1.2) the operator type(s) that play p in equilibrium σ are at least as well off and at least one is strictly better-off in equilibrium σ than in equilibrium σ': $\forall j \in K : E\Pi_j \geq E\Pi'_j$ and $\exists j \in K : E\Pi_j > E\Pi'_j$.
(D1.3) $\exists j_1 \in K$ s.t. manufacturer's belief about operator type j_1 after observing price p (i.e., $Pr(j_1|p)$) in equilibrium σ' is different from the conditional probabilities $\frac{Pr(j_1)\alpha_{j_1}}{Pr(j_1)\alpha_{j_1}+Pr(j_2)\alpha_{j_2}}$ with $\{j_1, j_2\} = \{E, I\}$ and
$\alpha_j = 1$ if $j \in K$ and $E\Pi_j > E\Pi'_j$
$\alpha_j \in [0, 1]$ if $j \in K$ and $E\Pi_j = E\Pi'_j$
$\alpha_j = 0$ if $j \notin K$.

Consider equilibrium σ with prices (p_E, p_I) chosen by type E and I on the equilibrium path and (Π_E, Π_I) as their expected profits. If $p_E = p_I$, σ is a pooling equilibrium and otherwise a separating equilibrium. (p'_E, p'_I) and (Π'_E, Π'_I) are the prices and profits on the equilibrium path of σ'.

Lemma 3. *When the manufacturer has the worst off-equilibrium beliefs, i.e., the operator is type I, let's consider σ and σ' coexisting for a given set of parameters. If the following conditions are satisfied, then σ defeats σ':*
(a) $p_E \notin \{p'_E, p'_I\}$
(b) $\Pi_E > \Pi'_E$ and, if $p_E = p_I$, $\Pi_I \geq \Pi'_I$.

Proof. Let K be the set of operator types which choose p_E in σ. When $p_E \neq p_I$, $K = \{E\}$ and, when $p_E = p_I$, $K = \{E, I\}$. Using Definition 1, we show when σ defeats

σ'. (D1.1) Condition (a) and $K \neq \varnothing$ mean that p_E is off-equilibrium path in σ' with at least one type of operator playing p_E in σ. (D1.2) The first part of condition (b) means that the expected profit of E is greater in σ than in σ'. The second part means that if σ is pooling, i.e., I also plays price p_E in σ, then I is no worse-off in σ than in σ'. (D1.3) In σ', p_E is off-equilibrium path and thus the manufacturer has the worst beliefs, i.e., the operator is of type I. This belief is different from the positive probability that type E selected p_E conditional on the operator's type $\in K$ (i.e., this probability is $\gamma/(\gamma + (1-\gamma)\alpha_I) > 0$ with $\alpha_I = 0$ if $I \notin K$, $\alpha_I = 1$ if $I \in K$ and $\Pi_I > \Pi'_I$, and $\alpha_I \in [0,1]$ if $I \in K$ and $\Pi_I = \Pi'_I$). □

We use the following endogenous off-equilibrium prices.

Period 3: When $\tilde{p} > p_H$, the operator believes $Pr[H|p_j \text{ accepted}] = 0$. If he is type I, he will then proceed to dump. When $\tilde{p} \leq p_H$, the operator believes $Pr[H|\tilde{p} \text{ accepted}] = h$ and if he is of type I, he then proceeds to treat. The profit maximising strategy of type E is to treat for any belief.

Period 2: Manufacturer of type H rejects when $\tilde{p} > p_H$ and of type L rejects when $\tilde{p} > p_L$. The manufacturer beliefs $\Pr[j = I|\tilde{p}]$=1 and, if she accepts $\tilde{p}$ at $t = 2$, $E\Pi_H(\text{Accept } \tilde{p}) = E\Pi_L(\text{Accept } \tilde{p})$, while if she rejects $E\Pi_H(\text{Reject } \tilde{p}) = -s_H > E\Pi_L(\text{Reject } \tilde{p}) = -s_L$. So, if type H accepts, L accepts; and if type L rejects, H rejects. It therefore must be that $p_H \leq p_L$.

Price $\tilde{p}$	Manufacturer H	Manufacturer L
$\tilde{p} \leq p_H \leq p_L$	$E\Pi(\text{Accept}) = -\tilde{p}$	$E\Pi(\text{Accept}) = -\tilde{p}$
$p_H < \tilde{p} \leq p_L$	$E\Pi(\text{Reject}) = -s_H$	$E\Pi(\text{Accept}) = -\tilde{p} - \delta$
$\tilde{p} > p_L$	$E\Pi(\text{Reject}) = -s_H$	$E\Pi(\text{Reject}) = -s_L$

Using the table, we can derive the conditions for the off-equilibrium prices: $H(\text{Accept iff } \tilde{p} \leq p_H)$ is true only if $\tilde{p} \leq s_H$ (to ensure $\tilde{p} \leq p_H$ is accepted) and $\tilde{p} \geq s_H - \delta$ (to ensure $\tilde{p} > p_H$ is rejected). $L(\text{Accept iff } \tilde{p} \leq p_L)$ is true only if $\tilde{p} \leq s_L$ (to ensure $\tilde{p} \leq p_H$ is accepted), $\tilde{p} \leq s_L - \delta$ (to ensure $p_H < \tilde{p} \leq p_L$ is accepted), and $\tilde{p} \geq s_L - \delta$ (to ensure $\tilde{p} > p_L$ is rejected). Thus, when $p_H < p_L$, it must be that $s_H - \delta \leq p_H \leq s_H$ and $p_L = s_L - \delta$. When $p_H = p_L$, it must be that $s_L - \delta \leq p_H = p_L \leq s_H$.

Before proving the results presented in the main paper, we characterise the equilibria in a series of lemmas. Lemmas 4 to 8 derive the necessary and sufficient conditions for equilibrium existence. If several equilibria of the same type exist and condition (a) in Lemma 3 holds, the undefeated equilibrium selects the one that yields the highest profit for the efficient treatment operator. Lemmas 9 to 17 give the necessary and sufficient conditions when there is multiplicity between equilibria of different types.

Lemma 4. Breakdown Equilibrium - weaker domestic enforcement (pooling):

1. *Both operator types choose p^* in period 1.*
2. *In period 2, the beliefs are $Pr[E|p^*] = \gamma$ and $Pr[E|\tilde{p}] = 0$ for $\tilde{p} \neq p^*$. Only Manufacturer L accepts p^*. If the price is $\tilde{p} \neq p^*$, both accept if $\tilde{p} \leq p_H$, both reject if $\tilde{p} > p_L$, and H rejects while L accepts if $p_H < \tilde{p} \leq p_L$.*
3. *In period 3, the beliefs are $Pr[H|p^* \text{ accepted}] = 0$, $Pr[H|\tilde{p} \text{ accepted}] = 0$ if $\tilde{p} > p_H$ and $Pr[H|\tilde{p} \text{ accepted}] = h$ if $\tilde{p} \leq p_H$. Operator E always treats while I dumps after p^*, but after $\tilde{p} \neq p^*$, I dumps iff $\tilde{p} > p_H$ and treats otherwise.*

With $p^* = s_L - (1-\gamma)\delta$, this equilibrium exists iff the following conditions are satisfied:

- $s_H - \delta \leq h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta)$
- $D \leq s_L - (1-\gamma)\delta$

Proof. **Period 3:** Regardless of waste quality, Operator E's profit maximizing strategy is to treat at $t = 3$. When the price is p^*, Operator I believes $Pr[H|p_j \text{ accepted}] = 0$, he will then proceed to dump.
Period 2: If the price is p^*, Manufacturer i believes $Pr[E|p^*] = \gamma$ and thus $E\pi_i(\text{Accept}) = -p^* - (1-\gamma)\delta$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p^* \leq s_i - (1-\gamma)\delta$ and rejects otherwise. Consequently, H rejects p^* and L accepts p^* iff $s_H - (1-\gamma)\delta < p^* \leq s_L - (1-\gamma)\delta$.
Period 1: For Operator E, setting p^* such that $s_H - (1-\gamma)\delta < p^* \leq s_L - (1-\gamma)\delta$ leads to $E\Pi_E = (1-h)(p^* + v_L - c_E)$, which cannot be smaller than the profits in any of the deviations:

- choosing $\tilde{p} \leq p_H$: $E\Pi_E = \tilde{p} + \overline{v} - c_E$,
- choosing $p_H < \tilde{p} \leq p_L$: $E\Pi_E = (1-h)(\tilde{p} + v_L - c_E)$,
- choosing $\tilde{p} > p_L$: $E\Pi_E = 0$.

For Operator I, setting p^* such that $s_H - (1-\gamma)\delta < p^* \leq s_L - (1-\gamma)\delta$ leads to $E\Pi_I = (1-h)(p^* - D)$, which cannot be smaller than the profits in any of the deviations:

- choosing $\tilde{p} \leq p_H$: $E\Pi_I = \tilde{p} + \overline{v} - c_I$,
- choosing $p_H < \tilde{p} \leq p_L$: $E\Pi_I = (1-h)(\tilde{p} - D)$,
- choosing $\tilde{p} > p_L$: $E\Pi_I = 0$.

Two cases emerge: $p_H < p_L$ and $p_H = p_L$. We take p_H and p_L as small as possible to relax the conditions. If there exists p^* and $\{p_H, p_L\}$ satisfying either set of conditions, this equilibrium exists:
$\rightarrow \quad s_H - (1-\gamma)\delta < p^* \leq s_L - (1-\gamma)\delta$

1. $p^* \geq c_E - v_L$ to guarantee $E\Pi_E \geq 0$;
2. $p^* \geq D$ to guarantee $E\Pi_I \geq 0$;

$p_H < p_L$

3. $s_H - \delta \leq h(c_E - v_H) + (1-h)p^*$ otherwise E deviates to $p_H = s_H - \delta$;
4. $s_H - \delta \leq c_I - \overline{v} + (1-h)(p^* - D)$ otherwise I deviates to $p_H = s_H - \delta$;
5. $s_L - \delta \leq p^*$ otherwise E and I deviate to $p_L = s_L - \delta$.

$p_H = p_L$

3. $s_L - \delta \leq h(c_E - v_H) + (1-h)p^*$ otherwise E deviates to $p_H = s_L - \delta$;
4. $s_L - \delta \leq c_I - \overline{v} + (1-h)(p^* - D)$ otherwise I deviates to $p_H = s_L - \delta$;
5. $s_L - \delta \leq s_H$ to guarantee $s_L - \delta \leq p_H = p_L \leq s_H$.

The undefeated Breakdown equilibrium must have $p^* = s_L - (1-\gamma)\delta$. Using Lemma 3, $\forall\ p' < s_L - (1-\gamma)\delta$ with $K = \{E, I\}$, $\Pi_E > \Pi'_E$ and $\Pi_I > \Pi'_I$. Condition (2) implies condition (1) per Assumption 1(i) $D \geq c_E - v_L$, and (3) implies (4) per Assumption 1(ii) $D < c_I - v_L$. Note that the set of conditions for $p_H < p_L$ is easiest to satisfy. $\square$

Lemma 5. Full Compliance Equilibrium (pooling)

1. *Both operator types choose p^* in period 1.*
2. *In period 2, the beliefs are $Pr[E|p^*] = \gamma$ and $Pr[E|\tilde{p}] = 0$ for $\tilde{p} \neq p^*$. Both manufacturer types accept p^*. If the price is $\tilde{p} \neq p^*$, both accept if $\tilde{p} \leq p_H$, both reject if $\tilde{p} > p_L$, and H rejects while L accepts if $p_H < \tilde{p} \leq p_L$.*
3. *In period 3, the beliefs are $Pr[H|p^* \text{ accepted}] = h$, $Pr[H|\tilde{p} \text{ accepted}] = 0$ if $\tilde{p} > p_H$ and $Pr[H|\tilde{p} \text{ accepted}] = h$ if $\tilde{p} \leq p_H$. Operator E always treats while I treats after p^*, but after $\tilde{p} \neq p^*$, I dumps iff $\tilde{p} > p_H$ and treats otherwise.*

With $p^* = s_H$, this equilibrium exists iff the following conditions are satisfied:

- $s_H \geq c_I - \overline{v}$
- $s_H \geq c_I - \overline{v} + (1-h)(s_L - \delta - D)$ *when* $s_H < s_L - \delta$

Proof. **Period 3:** Regardless of waste quality, Operator E's profit maximizing strategy is to treat at $t = 3$. When the price is p^*, Operator I believes $Pr[H|p_j \text{ accepted}] = h$; he will then proceed to treat.

Period 2: If the price is p^*, Manufacturer i believes $Pr[E|p^*] = \gamma$ and since both operator types treat in period 3, $E\pi_i(\text{Accept}) = -p^*$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p^* \leq s_i$ and rejects otherwise. Consequently, both manufacturer types accept p^* iff $p^* \leq s_H$.

Period 1: For Operator E, setting p^* such that $p^* \leq s_H$ leads to $E\Pi_E = p^* + \overline{v} - c_E$. For Operator I, setting p^* such that $p^* \leq s_H$ leads to $E\Pi_I = p^* + \overline{v} - c_I$. These profits cannot be smaller than the profits in any of the deviations outlined in Lemma 4.

We take p_H and p_L as small as possible when $p_H < p_L$ and when $p_H = p_L$ to relax the conditions. If there exists p^* and $\{p_H, p_L\}$ satisfying either set of conditions, this equilibrium exists:

$\rightarrow \quad p^* \leq s_H$

1. $p^* \geq c_E - \overline{v}$ to guarantee $E\Pi_E \geq 0$;
2. $p^* \geq c_I - \overline{v}$ to guarantee $E\Pi_I \geq 0$;

$p_H < p_L$

3. $p^* \geq s_H - \delta$ otherwise E and I deviate to $p_H = s_H - \delta$;
4. $p^* \geq h(c_E - v_H) + (1-h)(s_L - \delta)$ otherwise E deviates to $p_L = s_L - \delta$;
5. $p^* \geq c_I - \overline{v} + (1-h)(s_L - \delta - D)$ otherwise I deviates to $p_L = s_L - \delta$.

$p_H = p_L$

3. $p^* \geq s_L - \delta$ otherwise E and I deviate to $p_H = s_L - \delta$;
4. $s_L - \delta \leq s_H$ to guarantee $s_L - \delta \leq p_H = p_L \leq s_H$.

The undefeated Full Compliance equilibrium must have $p^* = s_H$. Using Lemma 3, $\forall\, p' < s_H$ with $K = \{E, I\}$, $\Pi_E > \Pi'_E$ and $\Pi_I > \Pi'_I$. Condition (2) implies (1) since $c_E < c_I$ and for the case $p_H < p_L$, condition (5) implies (4) per Assumption 1(ii) $D > c_I - v_L$. Condition (3) always holds with the undefeated price. □

Lemma 6. Partial Compliance Equilibrium - weak domestic enforcement (separating)

1. *Operator types E and I choose p^*_E and p^*_I respectively in period 1.*

2. *In period 2, the beliefs are $Pr[E|p^*_E] = 1$, $Pr[E|p^*_I] = 0$, and $Pr[E|\tilde{p}] = 0$ for $\tilde{p} \neq (p^*_E, p^*_I)$. Manufacturer H accepts p^*_E but rejects p^*_I and Manufacturer L accepts both p^*_E and p^*_I. If the price is $\tilde{p} \neq (p^*_E, p^*_I)$, both accept if $\tilde{p} \leq p_H$, both reject if $\tilde{p} > p_L$, and H rejects while L accepts if $p_H < \tilde{p} \leq p_L$.*

3. *In period 3, the beliefs are* $Pr[H|p_E^* \text{ accepted}] = h$, $Pr[H|p_I^* \text{ accepted}] = 0$, $Pr[H|\tilde{p} \text{ accepted}] = 0$ *if* $\tilde{p} > p_H$ *and* $Pr[H|\tilde{p} \text{ accepted}] = h$ *if* $\tilde{p} \leq p_H$. *Operator* E *always treats while* I *dumps after* p_I^*, *but after* $\tilde{p} \neq (p_E^*, p_I^*)$, I *dumps iff* $\tilde{p} > p_H$ *and treats otherwise.*

With $p_E^* = \min(s_H, c_I - \overline{v} + (1-h)(p_I^* - D))$ *and* $D \leq p_I^* \leq s_L - \delta$, *this equilibrium exists iff the following conditions are satisfied:*

- $p_E^* \geq s_H - \delta$
- $p_E^* \geq h(c_E - v_H) + (1-h)(s_L - \delta)$
- $p_I^* = s_L - \delta$ *when* $s_H < s_L - \delta$

Proof. **Period 3:** Regardless of waste quality, Operator E's profit maximizing strategy is to treat at $t = 3$. When the price is p_I^*, Operator I believes $Pr[H|p_j \text{ accepted}] = 0$; he will then proceed to dump. If the price is p_E^*, he believes the price is accepted by both manufacturer types ($Pr[H|p_E \text{ accepted}] = h$), then he proceeds to treat.
Period 2: If the price is p_E^*, Manufacturer i believes $Pr[E|p_E^*] = 1$ and thus $E\pi_i(\text{Accept}) = -p_E^*$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_E^* \leq s_i$ and rejects otherwise. Consequently, both manufacturer types accept p_E^* iff $p_E^* \leq s_H$.
If the price is p_I^*, Manufacturer i believes $Pr[E|p_I^*] = 0$ and thus $E\pi_i(\text{Accept}) = -p_I^* - \delta$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_I^* \leq s_i - \delta$ and rejects otherwise. Consequently, H rejects p_I^* and L accepts p_I^* iff $s_H - \delta < p_I^* \leq s_L - \delta$.
Period 1: For Operator E, setting p_E^* such that $p_E^* \leq s_H$ leads to $E\Pi_E = p_E^* + \overline{v} - c_E$. For Operator I, setting p_I^* such that $s_H - \delta < p_I^* \leq s_L - \delta$ leads to $E\Pi_I = (1-h)(p_I^* - D)$. These profits cannot be smaller than the profits in any of the deviations outlined in in Lemma 4.
We take p_H and p_L as small as possible when $p_H < p_L$ and when $p_H = p_L$ to relax the conditions. If there exists $\{p_E^*, p_I^*\}$ and $\{p_H, p_L\}$ satisfying either set of conditions, this equilibrium exists:
$\rightarrow$ $p_E^* \leq s_H$ and $s_H - \delta < p_I^* \leq s_L - \delta$

1. $p_E^* \geq h(c_E - v_H) + (1-h)p_I^*$ otherwise E deviates to $s_H - \delta < p_I^* \leq s_L - \delta$;
2. $p_E^* \geq c_E - \overline{v}$ to guarantee $E\Pi_E \geq 0$;
3. $p_E^* \leq c_I - \overline{v} + (1-h)(p_I^* - D)$ otherwise I deviates to $p_E^* \leq s_H$;
4. $p_I^* \geq D$ to guarantee $E\Pi_I \geq 0$;

$p_H < p_L$

5. $p_E^* \geq s_H - \delta$ otherwise E deviates to $p_H = s_H - \delta$;

6. $p_E^* \geq h(c_E - v_H) + (1-h)(s_L - \delta)$ otherwise E deviates to $\tilde{p} = s_L - \delta$;
7. $s_H - \delta \leq c_I - \overline{v} + (1-h)(p_I^* - D)$ otherwise I deviates to $p_H = s_H - \delta$;
8. $p_I^* \geq s_L - \delta$ otherwise I deviates to $p_L = s_L - \delta$.

$p_H = p_L$

5. $p_E^* \geq s_L - \delta$ otherwise E deviates to $p_H = s_L - \delta$;
6. $s_L - \delta \leq s_H$

The undefeated Partial Compliance equilibrium must have $p_E^* = \min\{s_H, c_I - \overline{v} + (1-h)(p_I^* - D)\}$. Using Lemma 3, $\forall\, p' < \min\{s_H, c_I - \overline{v} + (1-h)(p_I^* - D)\}$ with $K = \{E\}$, $\Pi_E > \Pi'_E$. When $s_H < s_L - \delta$, there exists a single undefeated Partial Compliance equilibrium with $p_I^* = s_L - \delta$. Otherwise, there are multiple with $p_I^* \leq s_L - \delta$. Condition (2) is implied by condition (1), condition (4), and Assumption 1(i) $D \geq c_E - v_L$. For the case $p_H < p_L$, conditions (3) and (5) imply condition (7); and condition (6) is implied by conditions (1) and (8). □

Lemma 7. Partial Compliance Equilibrium - strong domestic enforcement (separating)

1. *Operator types E and I choose p_E^* and p_I^* respectively in period 1.*
2. *In period 2, the beliefs are $Pr[E|p_E^*] = 1$, $Pr[E|p_I^*] = 0$, and $Pr[E|\tilde{p}] = 0$ for $\tilde{p} \neq (p_E^*, p_I^*)$. Both manufacturer types accept p_E^* and reject p_I^*. If the price is $\tilde{p} \neq (p_E^*, p_I^*)$, both accept if $\tilde{p} \leq p_H$, both reject if $\tilde{p} > p_L$, and H rejects while L accepts if $p_H < \tilde{p} \leq p_L$.*
3. *In period 3, the beliefs are $Pr[H|p_E^*$ accepted$] = h$ and $Pr[H|p_I^*$ accepted$] = 0$, $Pr[H|\tilde{p}$ accepted$] = 0$ if $\tilde{p} > p_H$ and $Pr[H|\tilde{p}$ accepted$] = h$ if $\tilde{p} \leq p_H$. Operator E always treats while I does not receive any waste after p_I^*, but after $\tilde{p} \neq (p_E^*, p_I^*)$, I dumps iff $\tilde{p} > p_H$ and treats otherwise.*

With $p_E^* = \min(s_H, c_I - \overline{v})$ and $p_I^* > s_L - \delta$, this equilibrium exists iff the following conditions are satisfied:

- $p_E^* \geq h(c_E - v_H) + (1-h)(s_L - \delta)$ *when* $s_H < s_L - \delta$
- $D \geq s_L - \delta$ *when* $s_H < s_L - \delta$
- $p_E^* \geq s_H - \delta$ *when* $s_H < s_L - \delta$

Proof. **Period 3:** Regardless of waste quality, Operator E's profit maximizing strategy is to treat at $t = 3$. When the price is p_E^*, Operator I believes $Pr[H|p_j$ accepted$] = h$; he will then proceed to treat. For p_I^* there can be two cases that lead to this equilibrium since I does not receive waste in equilibrium: (1) if beliefs are $Pr[H|p_I^*$ accepted$] = 0$, then Operator I proceeds to dump after p_I^*, and (2) if beliefs are $Pr[H|p_I^* \text{ accepted}] = h$, then Operator I treats after p_I^*.

Period 2: If the price is p_E^*, Manufacturer i believes $Pr[E|p_E^*] = 1$ and thus $E\pi_i(\text{Accept}) = -p_E^*$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_E^* \leq s_i$ and rejects otherwise. Consequently, both manufacturer types accept p_E^* iff $p_E^* \leq s_H$.

If the price is p_I^*, Manufacturer i believes $Pr[E|p_I^*] = 0$. If (1) $E\pi_i(\text{Accept}) = -p_I^* - \delta$ and $E\pi_i(\text{Reject}) = -s_i$ then she accepts for $p_I^* \leq s_i - \delta$ and rejects otherwise. If (2) $E\pi_i(\text{Accept}) = -p_I^*$ and $E\pi_i(\text{Reject}) = -s_i$ then she accepts for $p_I^* \leq s_i$ and rejects otherwise. Consequently, both manufacturer types reject p_I^* iff (1) $p_I^* > s_L - \delta$ or (2) $p_I^* > s_L$. We proceed with (1) without loss of generality.

Period 1: For Operator E, setting p_E^* such that $p_E^* \leq s_H$ leads to $E\Pi_E = p_E^* + \overline{v} - c_E$. For Operator I, setting p_I^* such that $p_I^* > s_L - \delta$ or $p_I^* > s_L$ leads to $E\Pi_I = 0$. These profits cannot be smaller than the profits in any of the deviations outlined in Proposition 1.

We take p_H and p_L as small as possible when $p_H < p_L$ and when $p_H = p_L$ to relax the conditions. If there exists $\{p_E^*, p_I^*\}$ and $\{p_H, p_L\}$ satisfying either set of conditions, this equilibrium exists:

$\rightarrow \quad p_E^* \leq s_H$ and $p_I^* > s_L - \delta$

1. $p_E^* \geq c_E - \overline{v}$ to guarantee $E\Pi_E \geq 0$;
2. $p_E^* \leq c_I - \overline{v}$ otherwise I deviates to $p_E^* \leq s_H$;

$p_H < p_L$

3. $p_E^* \geq s_H - \delta$ otherwise E deviates to $p_H = s_H - \delta$;
4. $s_H - \delta \leq c_I - \overline{v}$ otherwise I deviates to $p_H = s_H - \delta$;
5. $p_E^* \geq h(c_E - v_H) + (1-h)(s_L - \delta)$ otherwise E deviates to $p_L = s_L - \delta$;
6. $D \geq s_L - \delta$ otherwise I deviates to $p_L = s_L - \delta$.

$p_H = p_L$

3. $p_E^* \geq s_L - \delta$ otherwise E deviates to $p_H = s_L - \delta$;
4. $s_L - \delta \leq c_I - \overline{v}$ otherwise I deviates to $p_H = s_L - \delta$;
5. $s_H \geq s_L - \delta$ to guarantee $s_L - \delta \leq p_H = p_L \leq s_H$.

The undefeated Partial Compliance equilibrium must have $p_E^* = \min\{s_H, c_I - \overline{v}\}$ and any $p_I^* > s_L - \delta$ or $p_I^* > s_L$, depending on beliefs. Using Lemma 3, $\forall\, p' < \min\{s_H, c_I - \overline{v}\}$ with $K = \{E\}$, $\Pi_E > \Pi'_E$. Conditions (1) and (3) always hold and conditions (2) and (3) imply condition (4). $\square$

Lemma 8. Breakdown Equilibrium - strong domestic enforcement (separating)

1. *Operator types E and I choose p_E^* and p_I^* respectively in period 1.*

2. *In period 2, the beliefs are $Pr[E|p_E^*] = 1$, $Pr[E|p_I^*] = 0$, and $Pr[E|\tilde{p}] = 0$ for $\tilde{p} \neq (p_E^*, p_I^*)$. Manufacturer H rejects p_E^* and p_I^* while Manufacturer L accepts p_E^* and rejects p_I^*. If the price is $\tilde{p} \neq (p_E^*, p_I^*)$, both accept if $\tilde{p} \leq p_H$, both reject if $\tilde{p} > p_L$, and H rejects while L accepts if $p_H < \tilde{p} \leq p_L$.*

3. *In period 3, the beliefs are $Pr[H|p_E^*$ accepted$] = 0$ and $Pr[H|p_I^*$ accepted$] = 0$, $Pr[H|\tilde{p}$ accepted$] = 0$ if $\tilde{p} > p_H$ and $Pr[H|\tilde{p}$ accepted$] = h$ if $\tilde{p} \leq p_H$. Operator E always treats while I does not receive any waste after p_I^*, but after $\tilde{p} \neq (p_E^*, p_I^*)$, I dumps iff $\tilde{p} > p_H$ and treats otherwise.*[9]

With $s_H < p_E^* = \min(D, s_L)$ and $p_I^* > s_L - \delta$, this equilibrium exists iff the following conditions are satisfied:

- $D \geq s_L - \delta$
- $s_H - \delta \leq h(c_E - v_H) + (1 - h)p_E^*$

Proof. **Period 3:** Regardless of waste quality, Operator E's profit maximizing strategy is to treat at $t = 3$. When the price is p_E^*, Operator I believes $Pr[H|p_E^* \text{ accepted}] = 0$, he will then proceed to dump. Since I does not receive waste in equilibrium, there can be two cases for p_I^* that lead to this equilibrium: (1) if beliefs are $Pr[H|p_I^* \text{ accepted}] = 0$, then Operator I proceeds to dump after p_I^*, and (2) if beliefs are $Pr[H|p_I^* \text{ accepted}] = h$, then Operator I proceeds to treat after p_I^*.
Period 2: If the price is p_E^*, Manufacturer i believes $Pr[E|p_E^*] = 1$ and thus $E\pi_i(\text{Accept}) = -p_E^*$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_E^* \leq s_i$ and rejects otherwise. Consequently, only L accepts p_E^* iff $s_H < p_E^* \leq s_L$.
If the price is p_I^*, Manufacturer i believes $Pr[E|p_I^*] = 0$. If (1) then $E\pi_i(\text{Accept}) = -p_I^* - \delta$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_I^* \leq s_i - \delta$ and rejects otherwise. If (2) then $E\pi_i(\text{Accept}) = -p_I^*$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_I^* \leq s_i$ and rejects otherwise. Consequently, H and L reject p_I^* iff (1) $p_I^* > s_L - \delta$ or (2) $p_I^* > s_L$.
Period 1: For Operator E, setting p_E^* such that $s_H < p_E^* \leq s_L$ leads to $E\Pi_E = (1 - h)(p_E^* + v_L - c_E)$. For Operator I, setting p_I^* such that $p_I^* > s_L - \delta$ or $p_I^* > s_L$ leads

[9] Same results hold for $Pr[H|p_I^* \text{ accepted}] = h$, but then I must set $p_I^* > s_L$ instead of $p_I^* > s_L - \delta$

to $E\Pi_I = 0$. These profits cannot be smaller than the profits in any of the deviations outlined in Proposition 1.

We take p_H and p_L as small as possible when $p_H < p_L$ and when $p_H = p_L$ to relax the conditions. If there exists $\{p_E^*, p_I^*\}$ and $\{p_H, p_L\}$ satisfying either set of conditions, this equilibrium exists:

$\rightarrow \quad s_H < p_E^* \leq s_L$ and $p_I^* > s_L - \delta$

1. $p_E^* \geq c_E - v_L$ to guarantee $E\Pi_E \geq 0$;
2. $p_E^* \leq D$ otherwise I deviates to p_E^*;

$p_H < p_L$

3. $s_H - \delta \leq h(c_E - v_H) + (1-h)p_E^*$ otherwise E deviates to $p_H = s_H - \delta$;
4. $s_H - \delta \leq c_I - \overline{v}$ otherwise I deviates to $p_H = s_H - \delta$;
5. $p_E^* \geq s_L - \delta$ otherwise E deviates to $p_L = s_L - \delta$;
6. $s_L - \delta \leq D$ otherwise I deviates to $p_L = s_L - \delta$.

$p_H = p_L$

3. $s_L - \delta \leq h(c_E - v_H) + (1-h)p_E^*$ otherwise E deviates to $p_H = s_L - \delta$;
4. $s_L - \delta \leq c_I - \overline{v}$ otherwise I deviates to $p_H = s_L - \delta$;
5. $s_L - \delta \leq s_H$ to guarantee $s_L - \delta \leq p_H = p_L \leq s_H$.

The undefeated Breakdown equilibrium must have $p_E^* = \min(D, s_L)$ and any $p_I^* > s_L - \delta$ or $p_I^* > s_L$, depending on beliefs. Using Lemma 3, $\forall\ p' < \min\{D, s_L\}$ with $K = \{E\}$, $\Pi_E > \Pi'_E$. For $p_H < p_L$, conditions (2) and (3) imply condition (4) per Assumption 1(i) $D \geq c_E - v_L$, and conditions (2) and (5) imply condition (6). After refinement, condition (1) always holds per Assumption 1(i) $D \geq c_E - v_L$ and Assumption 2(ii) $s_L \geq c_E - v_L$. $\square$

Equilibria selection in case of coexistence

When equilibria characterised in Lemmas 4-8 coexist, we select the Pareto efficient equilibrium (if it exists) and apply the undefeated equilibrium refinement.

Lemma 9. Full Compliance vs Partial Compliance (weak) *When the equilibria coexist, Partial Compliance per Lemma 6 is defeated when (FC) holds and multiplicity remains when (FC) does not hold. As such, $p_E^* = s_H$ is the undefeated price in Partial Compliance.*

Proof. Using Lemma 3, let σ be a Partial Compliance equilibrium and σ' a Full Compliance equilibrium with $p'^* < p_E^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p_E^* + \overline{v} - c_E > \Pi'_E = p'^* + \overline{v} - c_E$, i.e., $p_E^* > p'^*$. Using the undefeated prices per Lemmas 5 and 6, Full Compliance defeats Partial Compliance in coexistence when $\min\{s_H, c_I - \overline{v} + (1-h)(p_I^* - D)\} > s_H$ which can never happen. Now let σ be a Full Compliance equilibrium and σ' a Partial Compliance equilibrium with $p^* > {p'_E}^*$ and $p^* \neq {p'_I}^*$ (satisfying (a)). σ defeats σ' in coexistence when $\Pi_E = p^* + \overline{v} - c_E > \Pi'_E = {p'_E}^* + \overline{v} - c_E$, i.e., ${p'_E}^* < p^*$, and $\Pi_I = p^* + \overline{v} - c_I \geq \Pi'_I = (1-h)({p'_I}^* - D)$, i.e., $p^* \geq c_I - \overline{v} + (1-h)({p'_I}^* - D)$. Using the undefeated prices, Full Compliance always defeats Partial Compliance when

$$s_H \geq c_I - \overline{v} + (1-h)(s_L - \delta - D). \tag{FC}$$

When (FC) does not hold, multiplicity may remain. Specifically, for $s_H \geq s_L - \delta$, there is multiplicity between Full Compliance and several Partial Compliance equilibria (see Lemma 6).

In the knife-edge case $s_H = c_I - \overline{v} + (1-h)(p_I^* - D)$, both are undefeated but Full Compliance Pareto dominates. The operator is indifferent regardless of type. If the manufacturer is of type H, she is indifferent as $p^* = {p'_E}^*$. If the manufacturer is of type L, she prefers Full Compliance as in Partial Compliance she can get matched with the more costly Operator I. $\square$

Lemma 10. Full Compliance vs Partial Compliance (strong) *When the equilibria coexist, Partial Compliance per Lemma 7 is defeated when $s_H \geq c_I - \overline{v}$. As such, $p_E^* = s_H$ is the undefeated price in Partial Compliance.*

Proof. Let σ be a Partial Compliance equilibrium and σ' a Full Compliance equilibrium with $p'^* > p_E^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p_E^* + \overline{v} - c_E > \Pi'_E = p'^* + \overline{v} - c_E$, i.e., $p_E^* > p'^*$. Using the undefeated prices per Lemmas 5 and 6, Full Compliance defeats Partial Compliance in coexistence when $\min\{s_H, c_I - \overline{v}\} > s_H$ which can never happen. Now let σ be a Full Compliance equilibrium and σ' a Partial Compliance equilibrium with $p^* > {p'_E}^*$ and $p^* \neq {p'_I}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p^* + \overline{v} - c_E > \Pi'_E = {p'_E}^* + \overline{v} - c_E$, i.e., ${p'_E}^* < p^*$, and $\Pi_I = p^* + \overline{v} - c_I \geq \Pi'_I = 0$, i.e., $p^* \geq c_I - \overline{v}$. Using the undefeated prices, Full Compliance defeats Partial Compliance in coexistence when $s_H > c_I - \overline{v}$. In the knife-edge case $s_H = c_I - \overline{v}$, both are undefeated but Full Compliance is efficient for the same reason as in Lemma 9. $\square$

Lemma 11. Full Compliance vs Breakdown (weak) *When the equilibria coexist, Full Compliance per Lemma 5 is defeated when* $s_H < h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta)$ *and Breakdown per Lemma 4 when* $s_H \geq c_I - \overline{v} + (1-h)(s_L - (1-\gamma)\delta$.

Proof. Let σ be a Breakdown equilibrium and σ' a Full Compliance equilibrium with $p^* > p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p^* + v_L - c_E) > \Pi'_E = p'^* + \overline{v} - c_E$, i.e., $p'^* < h(c_E - v_H) + (1-h)p^*$ and $\Pi_I = (1-h)(p^* - D) \geq \Pi'_I = p'^* + \overline{v} - c_I$. The first condition is binding per Assumption 1(ii). Using the undefeated prices per Lemmas 4 and 5, Breakdown defeats Full Compliance in coexistence when $s_H < h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta)$. Now, let σ be a Full Compliance equilibrium and σ' a Breakdown equilibrium with $p^* \notin p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p^* + \overline{v} - c_E > \Pi'_E = (1-h)(p'^* + v_L - c_E)$ and $\Pi_I = p^* + \overline{v} - c_I \geq \Pi'_I = (1-h)(p'^* - D) >$. The second condition is binding per Assumption 1(ii). Using the undefeated prices per Lemmas 4 and 5, Full Compliance defeats Breakdown in coexistence when $s_H \geq c_I - \overline{v} + (1-h)(s_L - (1-\gamma)\delta$. □

Lemma 12. Full Compliance vs Breakdown (strong) *When the equilibria coexist, Full Compliance per Lemma 5 defeats Breakdown per Lemma 8.*

Proof. Let σ be a Full Compliance equilibrium and σ' a Breakdown equilibrium with $p^* \neq p'_E{}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p^* + \overline{v} - c_E > \Pi'_E = (1-h)(p'_E{}^* + v_L - c_E)$, i.e., $p^* > h(c_E - v_H) + (1-h)p'_E{}^*$ and $\Pi_I = p^* + \overline{v} - c_I \geq \Pi'_I = 0$. The second condition is binding per Assumption 1(ii). Using the undefeated prices per Lemmas 4 and 5, Full Compliance defeats Breakdown when $s_H \geq c_I - \overline{v}$, which is whenever Full Compliance exists. Note that this condition is non-binding for Breakdown to be undefeated due to the (Bd-s) condition (to be discussed). □

Lemma 13. Partial Compliance (weak) vs Breakdown (weak) *When the equilibria coexist, Partial Compliance per Lemma 6 is defeated when (Bd) holds and Breakdown per Lemma 4 otherwise.*

Proof. Let σ be a Breakdown equilibrium and σ' a Partial Compliance equilibrium with $p^* > p'_E{}^*$ and $p^* > p'_I{}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p^* + v_L - c_E) > \Pi'_E = p'_E{}^* + \overline{v} - c_E$, i.e., $p'_E{}^* < h(c_E - v_H) + (1-h)p^*$ and $\Pi_I = (1-h)(p^* - D) \geq \Pi'_I = (1-h)(p'_I{}^* - D)$. Using the undefeated prices per Lemmas 4, 6, and 9, the latter restriction is always satisfied and thus Breakdown defeats Partial Compliance in coexistence when $s_H < h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta)$. Now, let σ be a Partial Compliance equilibrium and σ' a Breakdown equilibrium with $p^*_E \notin p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p'_E{}^* + \overline{v} - c_E > \Pi'_E = (1-h)(p'^* + v_L - c_E)$. Using the undefeated prices, Partial Compliance defeats Breakdown in coexistence when (Bd) does not hold and $D \leq s_L - \delta$. We break the equality in the knife-edge case $s_H = h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta)$ in favour of the preference of I, given that E is indifferent. Let

$$s_H \leq h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta). \tag{Bd}$$

□

Lemma 14. Partial Compliance (weak) vs Partial Compliance (strong) *When the equilibria coexist, Partial Compliance per Lemma 6 is efficient when $D \leq s_L - \delta$.*

Proof. Since the undefeated p_E^* is the same in these equilibria, neither is defeated. Using Pareto efficiency, we find that for $D < s_L - \delta$, operator of type I strictly prefers Partial Compliance (weak) and all other agents are indifferent. For $D = s_L - \gamma$, all agents are indifferent. From a global welfare standpoint, it can be argued that dumping of waste L in the country of origin is preferred over export. Let

$$D \leq s_L - \delta. \tag{3.1}$$

□

Lemma 15. Breakdown (weak) vs Breakdown (strong) *When the equilibria coexist, Breakdown per Lemma 8 is defeated when $D \leq s_L - (1-\gamma)\delta$.*

Proof. Let σ be a Breakdown (weak) equilibrium and σ' a Breakdown (strong) equilibrium with $p^* > p_E'^*$ and $p^* \neq p_I'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p^* + v_L - c_E) > \Pi'_E = (1-h)(p_E'^* + v_L - c_E)$ and $\Pi_I = (1-h)(p^* - D) \geq \Pi'_I = 0$. Using the undefeated prices per Lemmas 4 and 8 Breakdown (weak) defeats Breakdown (strong) in coexistence when $D < s_L - (1-\gamma)\delta$. For $D = (1-\gamma)\delta$, Breakdown (weak) is efficient due to manufacturer L's preference and the indifference of the other agents. Let

$$D \leq s_L - (1-\gamma)\delta. \tag{3.2}$$

□

Lemma 16. Breakdown (weak) vs Partial Compliance (strong) *When the equilibria coexist, Partial Compliance is defeated when (Bd) holds and Breakdown is defeated otherwise.*

Proof. Let σ be a Breakdown (weak) equilibrium and σ' a Partial Compliance (strong) equilibrium with $p^* > p_E'^*$ and $p^* \neq p_I'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p^* + v_L - c_E) > \Pi'_E = p_E'^* + \overline{v} - c_E$ and $\Pi_I = (1-h)(p^* - D) \geq \Pi'_I = 0$. Using the undefeated prices per Lemmas 4, 7, and 10 Breakdown defeats Partial Compliance in coexistence when (Bd) holds. Now, let σ be a Partial Compliance equilibrium and σ' a Breakdown equilibrium with $p_E^* \neq p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p_E^* + \overline{v} - c_E > \Pi'_E = (1-h)(p'^* + v_L - c_E)$, or when (Bd) does not hold. We break the equality in the knife-edge case $s_H = h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta)$ in favour of the preference of I, given that E is indifferent. $\square$

Lemma 17. Partial Compliance (strong) vs Breakdown (strong) *When the equilibria coexist, Breakdown per Lemma 8 is defeated when $s_H \geq h(c_E - v_H) + (1-h)\min\{D, s_L\}$ and Partial Compliance is defeated otherwise.*

Proof. Let σ be a Breakdown (strong) equilibrium and σ' a Partial Compliance (strong) equilibrium with $p_E^* > {p'_E}^*$ and $p_E^* \neq {p'_I}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p_E^* + v_L - c_E) > \Pi'_E = {p'_E}^* + \overline{v} - c_E$. Using the undefeated prices per Lemmas 8, 7, and 10 Breakdown defeats Partial Compliance when $s_H < h(c_E - v_H) + (1-h)\min\{D, s_L\}$. Now, let σ be a Partial Compliance equilibrium and σ' a Breakdown equilibrium with $p_E^* \neq {p'_E}^*$ and $p_E^* \neq {p'_I}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p_E^* + \overline{v} - c_E > \Pi'_E = (1-h)({p'_E}^* + v_L - c_E)$. In the knife-edge case $s_H = h(c_E - v_H) + (1-h)\min\{D, s_L\}$ Partial Compliance is efficient given the preference of manufacturer L and indifference of the other agents. Let

$$s_H < h(c_E - v_H) + (1-h)\min\{D, s_L\}. \tag{Bd-s}$$

$\square$

Proof of Proposition 1:

Proof. Combining Lemmas 4, 11, 13, 16 and 15 gives the following conditions for Breakdown (weak) to be the undefeated equilibrium (and efficient if it exists) when $D \leq s_L - \delta$:

- (Bd) holds: $s_H \leq h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta)$
- with $p^* = s_L - (1-\gamma)\delta$

To see what is necessary on the international policy side, we rewrite condition (Bd) under the least restrictive domestic policy values (i.e., $\delta = 0$): $s_H \leq h(c_E - v_H) + (1-h)s_L$. If $\delta > 0$, the range becomes larger in which the international policy climate leads to this equilibrium, but it can never be smaller. $\square$

Proof of Proposition 2:

Proof. Combining Lemmas 5, 9, 10, 11, and 12 give the following conditions for Full Compliance to be the undefeated equilibrium (and efficient if it exists) when $D \leq s_L - \delta$:

- (FC) holds: $s_H \geq c_I - \overline{v} + (1-h)(s_L - \delta - D)$
- (Bd) does not hold: $s_H > h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta)$
- with $p^* = s_H$

Full Compliance is *an* undefeated equilibrium when $s_H \geq s_L - \delta$, $s_H \geq c_I - \overline{v}$, (FC) does not hold, and (Bd) does not hold (with $p^* = s_H$).
The least restrictive necessary condition for this equilibrium that relies only on the international policies is $s_H \geq c_I - \overline{v}$ (see Lemma 5). □

Proof of Proposition 3:

Proof. Combining Lemmas 6, 9, 13, and 14 give the following conditions for Partial Compliance to be the undefeated (and efficient if it exists) equilibrium when $D \leq s_L - \delta$:

- $s_H < s_L - \delta$
- (FC) does not hold: $s_H < c_I - \overline{v} + (1-h)(s_L - \delta - D)$
- (Bd) does not hold: $s_H > h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta)$
- with $p_E^* = s_H$ and $p_I^* = s_L - \delta$

Partial Compliance is *an* undefeated equilibrium when $s_H \geq s_L - \delta$, (FC) does not hold, and (Bd) does not hold (with $p_E^* = s_H$ and $p_I^* \leq s_L - \delta$).
The least restrictive necessary condition for this equilibrium that relies only on the international policies is when $D \leq s_L - \delta$ and D and δ are at their minimum. Recall that per Assumption 1, our boundary condition is $D > \max\{0, c_E - v_L, c_I - \overline{v}\}$. Thus, we need $s_L - \delta + \frac{1}{1-h}(c_I - s_H - \overline{v}) > \max\{0, c_E - v_L, c_I - \overline{v}\}$. □

Proposition 4. *For $D + \delta > s_L$ and $D + (1-\gamma)\delta < s_L$:*
(i) the conditions for the Breakdown equilibrium are unchanged.
(ii) Full Compliance is the unique equilibrium iff $s_H \geq c_I - \overline{v}$ and ($\neg$ Bd), in which case both operator types set $p^* = s_H$ and treat all waste.
(iii) Partial Compliance is the unique equilibrium iff $s_H < c_I - \overline{v}$ and ($\neg$ Bd), in which case Operator I sets $p_I^* > s_L - \delta$ and receives no waste, and Operator E sets $p_E^* = s_H$ and treats all waste.

Proof. By combining Lemmas 4, 5, 7, 10, 11, 14, and 16 for $s_L - \delta < D \leq s_L - (1-\gamma)\delta$ the above conditions emerge. □

Proposition 5. *Under $D + (1-\gamma)\delta \geq s_L$,*
(i) Breakdown is the unique equilibrium iff (Bd-s) holds, in which case Operator I sets $p_I^* > s_L - \delta$ and receives no waste, and Operator E sets $p_E^* = \min\{D, s_L\}$ and treats waste L.
(ii) Full Compliance is the unique equilibrium iff $s_H \geq c_I - \overline{v}$, automatically satisfying ($\neg$ Bd-s).
(iii) Partial Compliance is the unique equilibrium iff $s_H < c_I - \overline{v}$ and ($\neg$ Bd-s), in which case Operator I sets $p_I^* > s_L - \delta$ and receives no waste, and Operator E sets $p_E^* = s_H$ and treats all waste.

Proof. By combining Lemmas 5, 7, 8, 10, 12, 15, and 17 for $D > s_L - (1-\gamma)\delta$ the above conditions emerge. □

3.8.3 Robustness of Results

Quality Verification by the Treatment Operator: We solve the game depicted in Figure 1, inserting a possibility for a quality verification at $t = 3$ before treating or dumping at $t = 4$ under incomplete information. We first determine the new incentives of the operator types at $t = 3$ and $t = 4$.
Periods 3 and 4: Operator E does not verify at $t = 3$ and treats the waste at $t = 4$. Operator I does not verify at $t = 3$ and dumps the waste at $t = 4$ if he believes $Pr[H|p_I \text{ accepted}] = 0$; Operator I verifies at $t = 3$ and dumps waste L and treats waste H at $t = 4$ if he believes $Pr[H|p_I \text{ accepted}] = h$ and $T < (1-h)(c + I - D - v_L)$ and does not verify at $t = 3$ and treats both wastes at $t = 4$ otherwise.

Proof. Regardless of waste quality, Operator E's profit maximising strategy is to treat at $t = 4$ (Assumption 1(i)). Identifying the waste quality therefore provides no benefit. When the price is such that Operator I believes $Pr[H|p_I \text{ accepted}] = 0$, he will dump without verification as identifying the quality provides no benefit (Assumption 1(ii)). When the price is such that Operator I believes $Pr[H|p_I \text{ accepted}] = h$, Operator I's expected profit when verifying the quality is $E\Pi_I(C) = p_I - h(c_I - v_H) - (1-h)D - T$. Operator I's expected profit when he doesn't verify (and thus treats both wastes per Assumption 1(iii)) is $\Pi_I(T) = p_I + hv_H + (1-h)v_L - c_I$. Thus, Operator I verifies the quality when $T < (1-h)(c_I - D - v_L)$ and does not verify and treat both wastes otherwise. In our original model, T is sufficiently high such that there is never an incentive to verify. □

The only equilibrium outcome that is affected is where Operator I believes $Pr[H|p_I \text{ accepted}] = h$. Thus, we re-establish Lemma 5 while Lemmas 4, 6, 7, and 8 remain unchanged. We assume $T = \epsilon < (1-h)(c_I - D - v_L)$ is negligible (very close to zero).

Lemma 18. Near-Full Compliance Equilibrium (pooling)

1. *Both operator types choose p^* in period 1.*
2. *In period 2, the beliefs are $Pr[E|p^*] = \gamma$ and $Pr[E|\tilde{p}] = 0$ for $\tilde{p} \neq p^*$. Both manufacturer types accept p^*. If the price is $\tilde{p} \neq p^*$, both accept if $\tilde{p} \leq p_H$, both reject if $\tilde{p} > p_L$, and H rejects while L accepts if $p_H < \tilde{p} \leq p_L$.*
3. *In period 3, the beliefs are $Pr[H|p^* \text{ accepted}] = h$, $Pr[H|\tilde{p} \text{ accepted}] = 0$ if $\tilde{p} > p_H$ and $Pr[H|\tilde{p} \text{ accepted}] = h$ if $\tilde{p} \leq p_H$. Operator E never verifies the quality. I verifies after p^*, while after $\tilde{p} \neq p^*$, he does not iff $\tilde{p} > p_H$ and verifies otherwise.*
4. *In period 4, Operator E treats regardless of quality, while I treats if, after p^* or $\tilde{p} \leq p_H$, the verification reveals waste H and dumps if the verification reveals waste L. Operator I dumps without verification when $\tilde{p} > p_H$.*

With $p^* = \min(s_H, s_L - (1-\gamma)\delta)$, this equilibrium exists iff p^* satisfies the following conditions:

- $p^* \geq h(c_I - v_H) + (1-h)D$
- $p^* \geq h(c_I - v_H) + (1-h)(s_L - \delta)$ *when* $s_H < s_L - \delta$

Proof. **Period 2:** If the price is p^*, Manufacturer i believes $Pr[E|p^*] = \gamma$ and since both operator types treat waste H in period 3, $E\pi_H(\text{Accept}) = -p^*$ and $E\pi_H(\text{Reject}) = -s_H$. Hence, H accepts for $p^* \leq s_H$ and rejects otherwise. Operator E treats L but Operator I verifies and dumps, so $E\pi_L(\text{Accept}) = -p^* - (1-\gamma)\delta$ and $E\pi_L(\text{Reject}) = -s_L$. Hence, L accepts for $p^* \leq s_L - (1-\gamma)\delta$ and rejects otherwise. **Period 1:** For Operator E, setting p^* such that $p^* \leq \min\{s_H, s_L - (1-\gamma)\delta\}$ leads to $E\Pi_E = p^* + \overline{v} - c_E$. For Operator I, setting p^* such that $p^* \leq \min\{s_H, s_L - (1-\gamma)\delta\}$ leads to $E\Pi_I = p^* - h(c_I - v_H) - (1-h)D$ where we assume $T \approx 0$. These profits cannot be smaller than the profits in any of the deviations outlined in Proposition 1.

We take p_H and p_L as small as possible when $p_H < p_L$ and when $p_H = p_L$ to relax the conditions. If there exists $\{p_E^*, p_I^*\}$ and $\{p_H, p_L\}$ satisfying either set of conditions, this equilibrium exists:

$\rightarrow \quad p^* \leq \min\{s_H, s_L - (1-\gamma)\delta\}$

1. $p^* \geq c_E - \overline{v}$ to guarantee $E\Pi_E \geq 0$;

2. $p^* \geq h(c_I - v_H) + (1-h)D$ to guarantee $E\Pi_I \geq 0$;

$p_H < p_L$

3. $p^* \geq s_H - \delta$ otherwise E deviates to $p_H = s_H - \delta$;
4. $p^* \geq s_H - \delta + (1-h)(v_L - c_I + D)$ otherwise I deviates to $p_H = s_H - \delta$;
5. $p^* \geq h(c_E - v_H) + (1-h)(s_L - \delta)$ otherwise E deviates to $p_L = s_L - \delta$;
6. $p^* \geq h(c_I - v_H) + (1-h)(s_L - \delta)$ otherwise I deviates to $p_L = s_L - \delta$;

$p_H = p_L$

3. $p^* \geq s_L - \delta$ otherwise E deviates to $p_H = s_L - \delta$;
4. $p^* \geq s_L - \delta + (1-h)(v_L - c_I + D)$ otherwise I deviates to $p_H = s_L - \delta$;
5. $s_L - \delta \leq s_H$ to guarantee $s_L - \delta \leq p_H = p_L \leq s_H$.

The undefeated Breakdown equilibrium must have $p^* = \min\{s_H, s_L - (1-\gamma)\delta\}$. Using Lemma 3, $\forall\ p' < \min\{s_H, s_L - (1-\gamma)\delta\}$ with $K = \{E, I\}$, $\Pi_E > \Pi'_E$ and $\Pi_I \geq \Pi'_I$. Condition (2) implies condition (1) per Assumption 1(i) $D \geq c_E - v_L$ and conditions (3) and (4) are always satisfied for the undefeated price (note that per Assumption 1(ii) $D < c_I - v_L$). For $p_H < p_L$, condition (6) implies (5) since $c_E < c_I$. □

Equilibria Selection in the Case of Coexistence

When the equilibria characterised in Lemmas 4, 6, 7, 8, and 18 coexist, we find the Pareto dominant one if it exists and apply the undefeated equilibrium refinement.

Lemma 19. Near-Full Compliance versus Partial Compliance (weak) *When the equilibria coexist, Near-Full Compliance is defeated when* $s_L-(1-\gamma) < \min\{s_H, c_I - \overline{v} + (1-h)(s_L - \delta - D)\}$. *Partial Compliance is defeated when* $c_I - \overline{v} + (1-h)(s_L - \delta - D) < \min\{s_H, s_L - (1-\gamma)\delta\}$ *and dominated when* $s_H < s_L - \delta$.

Proof. Let σ be a Near-Full Compliance equilibrium and σ' a Partial Compliance (weak) equilibrium with $p^* > {p'_E}^*$ and $p^* \neq {p'_I}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p^* + \overline{v} - c_E > \Pi'_E = p'^*_E + \overline{v} - c_E$ and $\Pi_I = p^* - h(c_I - v_H) - (1-h)D > \Pi'_I = (1-h)({p'_I}^* - D)$. Note that the latter condition is not binding as $c_I - v_L - D > {p'_I}^* - (s_L - \delta)$ per Assumption 1(ii): $D < c_I - v_L$. Using the undefeated prices per Lemmas 6 and 18 Near-Full Compliance defeats Partial Compliance when $\min\{s_H, s_L - (1-\gamma)\delta\} > \min\{s_H, c_I - \overline{v} + (1-h)(s_L - \delta - D\}$, or $c_I - \overline{v} + (1-h)(s_L - \delta - D) < \min\{s_H, s_L - (1-\gamma)\delta\}$. Now, let σ be a Partial Compliance equilibrium and σ' a Near-Full Compliance equilibrium with $p^*_E > p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p^*_E + \overline{v} - c_E > \Pi'_E = p'^* + \overline{v} - c_E$, or $s_L - (1-\gamma)\delta < \min\{s_H, c_I - \overline{v} + (1-h)(s_L - \delta - D)$. □

Lemma 20. Near-Full Compliance versus Partial Compliance (strong) *When the equilibria coexist, Near-Full Compliance is defeated when* $s_L - (1-\gamma) < \min\{s_H, c_I - \overline{v}\}$*. Partial Compliance is defeated when* $c_I - \overline{v} < \min\{s_H, s_L - (1-\gamma)\delta\}$ *and dominated when* $s_H < \min\{s_L - (1-\gamma)\delta, c_I - \overline{v}\}$*.*

Proof. Let σ be a Near-Full Compliance equilibrium and σ' a Partial Compliance (strong) equilibrium with $p^* > {p'_E}^*$ and $p^* \neq {p'_I}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p^* + \overline{v} - c_E > \Pi'_E = {p'_E}^* + \overline{v} - c_E$ and $\Pi_I = p^* - h(c_I - v_H) - (1-h)D > \Pi'_I = 0$. Note that the latter condition is one of the necessary conditions for Near-Full Compliance. Using the undefeated prices per Lemmas 7 and 18 Near-Full Compliance defeats Partial Compliance when $c_I - \overline{v} < \min\{s_H, s_L - (1-\gamma)\delta\}$. Now, let σ be a Partial Compliance equilibrium and σ' a Near-Full Compliance equilibrium with $p_E^* > p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p_E^* + \overline{v} - c_E > \Pi'_E = p'^* + \overline{v} - c_E$, or $s_L - (1-\gamma)\delta < \min\{s_H, c_I - \overline{v}$. When $p^* = p_E^* = s_H$, Near-Full Compliance is Pareto dominant when its necessary conditions are satisfied. □

Lemma 21. Near-Full Compliance versus Breakdown *When the equilibria coexist under* $D < s_L - (1-\gamma)\delta$*, Near-Full Compliance is defeated when (Bd) holds and Breakdown otherwise. When the equilibria coexist under* $D \geq s_L - (1-\gamma)\delta$*, Near-Full Compliance is defeated when* $s_H < h(c_E - v_H) + (1-h)\min\{D, s_L\}$ *and Breakdown otherwise.*

Proof. For $D \leq s_L - (1-\gamma)\delta$, let σ be a Breakdown (weak) equilibrium and σ' a Near-Full Compliance equilibrium with $p^* \neq p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p^* + v_L - c_E) > \Pi'_E = p'^* + \overline{v} - c_E$, i.e., $s_H < h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta$, and $\Pi_I = (1-h)(p^* - D) > \Pi'_I = p'^* - h(c_I - v_H) - (1-h)D$, which is not binding. We break the equality in the knife-edge case $s_H = h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta$ in favour of I's preference as E is indifferent. Letting σ be a Near-Full Compliance equilibrium and σ' a Breakdown equilibrium, we find that Breakdown is defeated when $s_H \geq h(c_I - v_H) + (1-h)(s_{L(}1-\gamma)\delta$, but note that Breakdown is already defeated when (Bd) does not hold per Lemma 13. For $D > s_L - (1-\gamma)\delta$, let σ be a Breakdown (weak) equilibrium and σ' a Near-Full Compliance equilibrium with $p_E^* \neq p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p_E^* + v_L - c_E) > \Pi'_E = p'^* + \overline{v} - c_E$, i.e., $\min\{s_H, s_L - (1-\gamma)\delta\} < h(c_E - v_H) + (1-h)\min\{D, s_L\}$. Note that if $s_H > h(c_E - v_H) + (1-h)\min\{D, s_L\}$, Breakdown is defeated per Lemma 17. Thus, Breakdown only defeats Near-Full Compliance when $s_H < h(c_E - v_H) + (1-h)\min\{D, s_L\}$. Letting σ be a Near-Full Compliance equilibrium and σ' a Breakdown equilibrium, we find that Breakdown is defeated when $s_H > h(c_I - v_H) + (1-h)\min\{D, s_L\}$. In equality, Near-Full Compliance is dominant given the preference of I and L. Let

$$s_H < h(c_E - v_H) + (1-h)\min\{D, s_L\}. \tag{Bd-s}$$

□

Proposition 6. Equilibrium conditions with quality verification *Under* $D \leq s_L - \delta$

- $s_H \leq s_L - (1-\gamma)\delta$
  - *Breakdown is the unique equilibrium iff (Bd) holds*
  - *Near-Full Compliance is an equilibrium iff (¬Bd) and is a unique equilibrium iff* $s_H > c_I - \overline{v} + (1-h)(s_L - \delta - D)$ *and (¬Bd)*
  - *Partial Compliance is an equilibrium iff* $s_H \leq c_I - \overline{v} + (1-h)(s_L - \delta - D)$ *and (¬Bd)*
- $s_H > s_L - (1-\gamma)\delta$
  - *Near-Full Compliance is the unique equilibrium iff* $c_I - \overline{v} + (1-h)(s_L - \delta - D) \leq s_L - (1-\gamma)\delta$[10]
  - *Partial Compliance is the unique equilibrium iff* $c_I - \overline{v} + (1-h)(s_L - \delta - D) > s_L - (1-\gamma)\delta$

Under $s_L - \delta < D < s_L - (1-\gamma)\delta$

- $s_H \leq s_L - (1-\gamma)\delta$
  - *Breakdown is the unique equilibrium iff (Bd) holds*
  - *Near-Full Compliance is the unique equilibrium iff* $s_H \geq h(c_I - v_H) + (1-h)D$ *and (¬Bd)*
  - *Partial Compliance is the unique equilibrium iff* $s_H < h(c_I - v_H) + (1-h)D$ *and (¬Bd)*
- $s_H > s_L - (1-\gamma)\delta$
  - *Near-Full Compliance is the unique equilibrium iff* $c_I - \overline{v} + (1-h)(s_L - \delta - D) \leq s_L - (1-\gamma)\delta$
  - *Partial Compliance is the unique equilibrium iff* $c_I - \overline{v} + (1-h)(s_L - \delta - D) > s_L - (1-\gamma)\delta$

Under $D > s_L - (1-\gamma)\delta$

[10] In the knife-edge case where this is equal, we select according to the preference of I as E is indifferent.

- $s_H \leq s_L - (1-\gamma)\delta$
  - *Breakdown is the unique equilibrium iff (Bd-s) holds*
  - *Near-Full Compliance is the unique equilibrium iff* $s_H \geq h(c_I - v_H) + (1-h)D$ *and* ($\neg$*Bd-s*)
  - *Partial Compliance is the unique equilibrium iff* $s_H < h(c_I - v_H) + (1-h)D$ *and* ($\neg$*Bd-s*)
- $s_H > s_L - (1-\gamma)\delta$
  - *Breakdown is the unique equilibrium iff (Bd-s) holds*
  - *Near-Full Compliance is the unique equilibrium iff* $c_I - \overline{v} \leq s_L - (1-\gamma)\delta$ *and* ($\neg$*Bd-s*)
  - *Partial Compliance is the unique equilibrium iff* $c_I - \overline{v} > s_L - (1-\gamma)\delta$ *and* ($\neg$*Bd-s*)

Proof. We combine the necessary and sufficient conditions for Near-Full Compliance (Lemma 18), Partial Compliance (Lemmas 6 and 7), and Breakdown (Lemmas 4 and 8) equilibria with the coexistence conditions, replacing the Lemmas referring to Full Compliance with Lemmas 19, 20, and 21. □

Quality uncertainty: The true waste quality remains H or L with probability h and $1-h$ respectively, but manufacturer i now observes $\tilde{H}$ or $\tilde{L}$, i.e., $i \in (\tilde{H}, \tilde{L})$. Thus, a manufacturer with waste H observes $\tilde{H}$ with probability α, or 'misidentifies' herself as type $\tilde{L}$ with probability $1-\alpha$. Similarly, a manufacturer with waste L observes $\tilde{L}$ with probability α and $\tilde{H}$ with probability $1-\alpha$. The probability of observing type $\tilde{H}$ is therefore $\tilde{h} = h\alpha + (1-h)(1-\alpha)$ and of type $\tilde{L}$ is $1-\tilde{h} = h(1-\alpha) + (1-h)\alpha$. The probability of having high-quality waste when observing $\tilde{H}$ is $Pr[H|\tilde{H}] = \frac{h\alpha}{\tilde{h}}$ and the probability of having low-quality waste when observing $\tilde{H}$ is $Pr[L|\tilde{H}] = \frac{(1-h)(1-\alpha)}{\tilde{h}}$. For the signal to be informative, we let $\alpha > 0.5$. Note that in our original model, $\alpha = 1$.

We want to study the effects of information asymmetry in a similar market as our original model, but now with uncertainty. We update the conditions in Assumptions 1 and 2 by redefining the recovery value parameters as $v_{\tilde{L}} = \frac{h(1-\alpha)}{1-\tilde{h}} v_H + \frac{(1-h)\alpha}{1-\tilde{h}} v_L$ and $v_{\tilde{H}} = \frac{h\alpha}{\tilde{h}} v_H + \frac{(1-h)(1-\alpha)}{\tilde{h}} v_L$. Per Assumption 2, the treatment operator must be able to charge a price in the first stage that makes treatment profitable in the third stage. The cost of the outside option translates into $s_{\tilde{H}} = \frac{h\alpha}{\tilde{h}} s_H + \frac{(1-h)(1-\alpha)}{\tilde{h}} s_L$ and $s_{\tilde{L}} = \frac{(h(1-\alpha)}{1-\tilde{h}} s_H + \frac{(1-h)\alpha}{1-\tilde{h}} s_L$. Thus, we get

Assumption 1 (b)**.** (i) $D \geq c_E - v_{\tilde{L}}$; (ii) $D < c_I - v_{\tilde{L}}$ (iii) $D \geq c_I - hv_H - (1-h)v_L$.

Note that (iii) is the same as $D > c_I - \tilde{h}v_{\tilde{H}} - (1-\tilde{h})v_{\tilde{L}}$.

Assumption 2 (b)**.** (i) $s_{\tilde{H}} \geq c_I - v_{\tilde{H}}$; (ii) $s_{\tilde{L}} \geq c_E - v_{\tilde{L}}$.

We solve the benchmark case where all agents have the same information to ensure the same waste outcomes are obtained as in our original model. Recall that in this benchmark, the manufacturer and treatment operator only observe $\tilde{H}$ or $\tilde{L}$ and are uncertain about the true waste quality.

Period 3: If Treatment Operator j treats the waste, his profit will be $\Pi_j(T) = p^* + Pr[H|\tilde{H}] \times v_H + Pr[L|\tilde{H}] \times v_L - c_j$. If he dumps it, his profit will be $\Pi_j(P) = p^* - D$. Treatment Operator j treats waste i iff $\Pi_j(T) \leq \Pi_j(P)$, i.e., iff $D \geq c_j - \frac{h\alpha}{\tilde{h}} \times v_H - \frac{(1-h)(1-\alpha)}{\tilde{h}} \times v_L$. Under Assumption 1a, the operator treats in period 3 when $(i,j) \in \{(\tilde{H},E),(\tilde{H},I),(\tilde{L},E)\}$, and dumps in period 3 when $(i,j) = (\tilde{L},I)$.
Period 2: Manufacturer i minimises her cost by accepting Operator j's price if $p_j \leq s_i$ when $(i,j) \in \{(\tilde{H},E),(\tilde{H},I),(\tilde{L},E)\}$ and if $p_j \leq s_i - \delta$ when $(i,j) = (\tilde{L},I)$.
Period 1: When $(i,j) \in \{(\tilde{H},E),(\tilde{H},I)$, Treatment Operator j's profit is $\Pi_j(T) = p_j + Pr[H|\tilde{H}] \times v_H + Pr[L|\tilde{H}] \times v_L - c_j$ if he sets $p_j \leq s_{\tilde{H}} = Pr[H|\tilde{H}] \times s_H + Pr[L|\tilde{H}] \times s_L$ and $\Pi_j(X) = 0$ otherwise. When $(i,j) = (\tilde{L},E)$, Treatment Operator E gains $\Pi_E(T) = p_E + Pr[H|\tilde{L}] \times v_H + Pr[L|\tilde{L}] \times v_L - c_E$ if he sets $p_E \leq s_{\tilde{L}} = Pr[H|\tilde{L}] \times s_H + Pr[L|\tilde{L}] \times s_L$ and $\Pi_j(X) = 0$ otherwise. Under Assumption 2b, $s_{\tilde{H}} \geq c_I - v_{\tilde{H}}$ and $s_{\tilde{L}} \geq c_E - v_{\tilde{L}}$ hold. Therefore, when $(i,j) \in \{(\tilde{H},E),(\tilde{H},I),(\tilde{L},E)$, both operator types set $p^*_j = s_{\tilde{H}}$ when waste quality is $\tilde{H}$ and $p^*_j = s_{\tilde{L}}$ when waste quality is $\tilde{L}$.
When $(i,j) = (\tilde{L},I)$, Treatment Operator I's profit is $\Pi_I(P) = p_I - D$ if he sets $p_I \leq s_{\tilde{L}} - \delta$ and $\Pi_I(P) = 0$ otherwise. Thus, for $D \leq s_{\tilde{L}}$, he charges $p^*_I = s_{\tilde{L}} - \delta$ and for $D > s_{\tilde{L}}$ he charges a fee that will not be accepted, $p^*_I > s_{\tilde{L}} - \delta$.

When we solve the game under incomplete information, we follow the same logic and redefine probability h and $1-h$ as $\tilde{h}$ and $1-\tilde{h}$. The conditions shift as e.g. $s_H < s_{\tilde{H}}$ and $s_L > s_{\tilde{L}}$, but the extension provides the same equilibrium outcomes (Breakdown, Full Compliance, Partial Compliance) and policy implications as the original model.

Note that $Pr[H|\tilde{H}] = \frac{h\alpha}{\tilde{h}} > Pr[H|\tilde{L}] = \frac{h(1-\alpha)}{1-\tilde{h}}$ iff $\alpha > 0.5$. The informative signal ensures that the outside option (s_i) of Manufacturer $\tilde{L}$ is costlier than the outside option of Manufacturer $\tilde{H}$ and the expected recovery value (v_i) of treating Manufacturer $\tilde{H}$ is higher than that of treating $\tilde{L}$.

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Chapter 4

Portfolios of the Poor: How Livelihood Compositions Shape Poverty Outcomes in Rural Villages

Extreme poverty continues to be overwhelmingly rural and smallholder farmers make up the majority of the world's poor. The importance of addressing rural smallholder poverty in a sustainable manner is self-evident. With that motivation, this paper seeks to understand better how livelihood portfolios of rural households bear upon rural poverty. Using a sample of over 4,000 smallholder households spanning 16 developing countries, we explore the poverty impact of compositional aspects of household income, explicitly differentiating between income derived from environmental, farm, and off-farm sources. We find that portfolio composition is a significant determinant of poverty, with some portfolios having poverty alleviating effects while others tend to exacerbate poverty at the village level. Notably, some portfolios that feature income sources that fall within the same broad-level category (environment, farm, off-farm) often affect poverty in opposing ways. Our findings have important implications for operational interventions or responsible sourcing strategies and their design for impact. A system-wide perspective is necessary to control for the dependencies between livelihood components that make up smallholder portfolios and to understand their effect on village-level poverty. This need becomes especially relevant as more firms and agencies source directly, simultaneously, but independently from each other, continuously affecting rural smallholders' livelihood composition.

4.1 Introduction

Eradicating poverty without imposing disproportionate pressure on the environment is a fundamental objective of the Sustainable Development Goals (SDGs). Moreover, hundreds of multinational firms have made commitments toward responsible sourcing and poverty eradication (Thorlakson et al., 2018). Since over 70% of the poor live in rural areas in developing countries and smallholder farmers are among the poorest (World Bank, 2018), the importance of addressing rural smallholder poverty in a sustainable manner is self-evident. It should also be remembered that small scale farmers in developing countries have been hit the hardest by the recent corona crisis (United Nations, 2020), raising the urgency of advancing the poverty agenda.

Farming is a key facet of livelihoods for rural smallholders and, as such, is considered an important target to alleviate poverty while at the same time securing a sustainable supply of key agricultural commodities. For example, the direct sourcing of agricultural products from smallholders has been used to expand a firm's supply base, but also to facilitate better prices for smallholders by eliminating middlemen and improving quality and productivity (De Zegher et al., 2019; IFC, 2013). Contract farming — a preharvest agreement between farmers and buyers — is also understood to be a useful tool to improve market access and farming profits (Federgruen et al., 2019; Meemken and Bellemare, 2020). Rural smallholders, however, typically undertake multiple economic activities that contribute to their income (FAO, 2015). Nowadays, off-farm income such as wage employment, small business enterprise, and even remittances have become an integral part of livelihood portfolios in smallholder settings. Social enterprises are rapidly emerging to help improve the living standards of the rural poor by e.g. linking the small business entrepreneurs to global markets (Sodhi and Tang, 2014). In addition to farm and off-farm income, studies have shown that smallholders in developing countries rely heavily on the environment, through e.g. products collected in forests and rivers, to complement their farming income (World Bank Group, 2016). Small and medium forest enterprises (SMFEs) are being established in developing countries – these are small entities designed to help the rural poor generate income from forest-related activities (by e.g. procuring products from the Açai palm and Baobab tree for cosmetics) (FAO and UNEP, 2020). One success story is the Farmer Managed Natural Regeneration (FMNG) programme in Niger which develops sustainable tree product value chains for communities to improve livelihoods (UNDESA, 2020). Yet, income from environmental sources is still rarely measured or considered in poverty studies, despite its importance for rural livelihoods (Angelsen et al., 2011; Wunder et al., 2014).

The fact that smallholders have multiple income sources and multiple ways of earning income is non-trivial for organisations concerned with poverty alleviation. Smallholders make independent choices of livelihood activities, which means that interventions such as those outlined above impact not only income levels of the targeted smallholders, but also the village level composition of livelihood portfolios. Moreover, since the economic activities are intricately related with one another and exhibit externalities, changes in livelihood portfolios can affect village poverty in unexpected ways. For instance, greater market access to and prices for farming products in developing countries has benefited billions of households, but at the same time, the resulting agricultural expansion comes at the expense of nearby natural resources. As the demand for land-intensive production grows and more smallholders convert forests to cropland and pasture, households with environmental resources in their livelihood portfolios will tend to be negatively affected (Sunderlin et al., 2005). Improved off-farm based income opportunities, such as those supported by social enterprises, have similarly raised rural income levels, but unlike agriculture, these activities shift occupational patterns away from land-intensive production and thus tend to reduce pressure on natural resources (FAO and UNEP, 2020). As some smallholders include more off-farm opportunities in their portfolios, others who continue to rely on the natural environment may also benefit from this shift.

The point of departure for this paper is to understand the extent to which the effectiveness of interventions in reducing poverty depends not only on changes in the village mean level of income, which is often the target of poverty interventions, but also on the underlying village wide composition of that income.

Against this background, we wish to answer the question whether the underlying composition of income (i.e., livelihood portfolios) matters for rural village level poverty and, if so, which particular combinations of income sources are associated with lower poverty rates. We address this question using a sample of over 4,000 smallholder households across 80 villages in 16 developing countries. We draw inferences about the effect of portfolios on village poverty using two constructs of poverty.

Our portfolio definition explicitly differentiates between income derived from environmental, farm, and off-farm sources. Environmental income is derived from selling or consuming products from natural resources (land that is not cultivated), including products like timber, wild meat, and fruits. Farm income comes from cultivated lands and includes the sale and consumption of crops and livestock. Off-farm sources include income derived from wage employment, small business enterprise and other sources such as pensions and remittances.

Our demarcation of livelihood portfolios first identifies, using cluster analysis, the set of main livelihood configurations the smallholders in our sample pursue. Then we derive the village-level distribution of smallholder cluster membership, i.e., the extent to which the identified livelihood configurations are pursued in each village. Essentially, the last step converts the household-level portfolio to a village-level configuration. This is necessary as poverty, by definition, is a community construct whereas livelihood portfolios are configured at the household level.

Poverty is our dependent variable and is measured with the headcount ratio, which is based on the proportion of households in the village that fall below the poverty line; and the poverty gap ratio, which weights the incomes of poor households by how far they fall below that line. Clearly, these measures are related, but focus on different parts of the income distribution. The poverty headcount is (only) sensitive to changes in income that lift people out of poverty, i.e., changes that *reduce* poverty by moving people above the poverty line. The poverty gap ratio is sensitive to changes in the incomes of the poorest which may *alleviate* poverty, i.e., changes in income that improve the well-being of the poor, but may not necessarily lift people above the poverty line. In summary, we focus on the impact of livelihood portfolios on poverty reduction (headcount) and poverty alleviation (gap).

We find that the composition of livelihood portfolios matters for village level poverty. Certain portfolios are strongly associated with reduction and alleviation of poverty, while others are closely associated with poverty exacerbation. This finding is all the more important as livelihood portfolios that contain dominant income sources within the same broad-level category (environment, farm, off-farm) often affect poverty in conflicting directions. More specifically, business income, as part of the off-farm category, is a key pathway out of poverty for the village. In contrast, villages where wage income is relatively dominant in portfolios tend to have a higher poverty headcount and gap. Our findings also suggest that forests should feature more prominently in general poverty alleviation strategies, while a higher reliance on extractive activities from non-forest environmental sources tends to exacerbate village poverty.

Given our results, we recommend monitoring compositional changes when poverty targeted interventions are applied. As such, we believe that a systemic approach that manages income components and portfolios simultaneously, rather than focusing on a single sub-component or on a subset of smallholders, is a more effective route to poverty alleviation. Currently, a business-case for sustainable supply chains is developed to aggregate supply and demand of agricultural products. Smallholders in a specific region are aggregated into a 'Producer Organisation' to simplify the direct sourcing of agricultural products as firms do not need to deal with smallholders, one-on-one (IFC, 2013). It is obvious that the efficacy of livelihood interventions as well as procurement strategies aiming to achieve prosperity can be meaningfully enhanced by extending smallholder aggregation beyond just agricultural products. For instance, village leaders or councils could play a role in aggregating and coordinating the demands from firms, social enterprises, and SMFEs for the different smallholder livelihood activities within a region. The need to coordinate becomes especially relevant as more firms and agencies source directly, simultaneously, but independently from each other.

We contribute to existing poverty studies by considering the compositional effect of income on village level poverty. This is novel as development economics studies tend to focus on the roles of the mean and distribution of total income in poverty alleviation, regardless of the source (e.g., Bluhm et al. (2018)). As such, governments and other international agencies should bring livelihood portfolios to the forefront of poverty alleviation strategies.

Operations management takes a more micro-oriented view and tends to focus on improving the level of income from specific sources, such as farming and business, through operational levers (e.g. De Zegher et al. (2019); Tang (2018)). Improving income from a specific source ignoring other sources and the portfolio composition can, however, lead to counter-intuitive outcomes. Thus the compositional question is novel also from an operations management perspective in considering the effect on poverty when the relative contributions of income from different sources changes.

From a methodological standpoint, we contribute through the development of a framework to analyse the effects of compositional data. We combine the additive logratios (alr), a transformation widely used for compositional data, with two methods that combat the problem of zero values, which are especially common in income data from developing countries and from agricultural settings. Moreover, poverty rates and the severity of poverty have been found to differ to some extent between Africa and Asia (World Bank, 2018), complicating any analysis that is aimed at defining more generally applicable strategies for poverty reduction. We therefore extend Ibragimov and Müller (2010) to regressions to conduct robust inference about population parameters that apply across both regions.

The rest of the paper is organised as follows. In section 2 we present the related literature and in section 3 the description of the data. Section 4 describes the model setup, including the approach for obtaining the two dimensions of livelihood portfolios, the construction of the compositional data, and the estimation framework. Section 5 covers the regression results and section 6 concludes with a discussion of the results and practical implications.

4.2 Literature

In the economics literature, there has been extensive research into poverty alleviation. Research typically studies the link between the responsiveness of a country's poverty level, income growth and changes in income inequality or redistribution (Bluhm et al., 2018; Dollar et al., 2016; Kalwij and Verschoor, 2007). These studies find that income growth does reduce poverty, but the responsiveness of poverty to that growth differs depending on a country's income characteristics, i.e. the income distribution, initial income level, and in which income quintile the growth is dominant.

This stream of literature has not yet sought to understand how income portfolios have a role to play in determining poverty. The studies generally use aggregated data that is measured yearly, and, though panel data is highly desirable for causal inferences, this structure does not allow an analysis of compositional effects. It thus reveals how given changes in aggregate income and distribution translate into poverty outcomes, but is silent on what ultimately determines poverty. Our data set contains detailed information on each household's income derivation, either for consumption or cash, as well as socioeconomic data. Note that because of this level of detail, it is available for a single year, though measured four times in that year to account for seasonality. Instead of looking at general income growth, we look at for which livelihood strategies we should be promoting growth to alleviate poverty. López-Feldman (2014) made a first suggestion that environmental income influences poverty, but only calculated that effect by including and excluding that component from total income in poverty measures. In practice, this may not represent common livelihood configurations nor would the exclusion of environmental income be independent from changes in other livelihood proportions.

Aggregated income data has several other drawbacks which can be overcome with our data set. First, inferences may guide macroeconomic policies, but may not be applicable to each part of the population. Especially in developing countries, it can be argued that a micro-level approach is more appropriate because there exists major differences between rural and urban populations. Moreover, in our analysis we do not have to make any assumptions about the underlying income distribution in a region since we have information on household income, rather than having only income information in the aggregate. Secondly, oftentimes there exist measurement differences in income and consumption across countries since a unified survey is not used, complicating cross-country comparisons. Since the same survey and definitions are used across countries in our data set, we can make cross-country comparisons more easily. Lastly, our survey contains data on production for own consumption. These non-marketed goods are a type of income that is widely overlooked in country level data since it is not converted to cash, but of particular importance to the rural poor. In summary, we can provide a portfolio and project selection perspective to the poverty literature by analysing the responsiveness of poverty with respect to the underlying composition of income, marketed or non-marketed, focusing on rural populations where poverty is most pronounced across range of developing countries.

In the rural livelihood literature within development economics, there have several studies on livelihood portfolios. Many of these studies focus on the role of diversification within portfolios in rural wealth, rather than the portfolios themselves (Duchelle et al., 2014; Martin and Lorenzen, 2016). Results suggest that portfolios are generally constructed of a combination between agricultural and non-agricultural activities but the level of diversification and the specialisation strategy depend on the level of wealth. In terms of the effect of the income components on wealth, Nielsen et al. (2013) compared livelihood portfolios and their determinants across three developing countries. The authors find that some elements of the common livelihood configurations, derived from K-means clustering, differ between the countries. The authors briefly explore the relationship between household wealth and cluster membership by the pairwise testing of income levels between groups (within each country) and suggest that, based on mean income differences, some strategies should be preferred over others if households strive to maximise income. However, to allow for pair-wise comparisons, the same number of partitions had to be selected for each country, whether appropriate or not, which also means that the comparison may have been between local optima rather than the global optimum. Nguyen et al. (2015) similarly use cluster analysis to construct livelihood portfolios in Cambodia and study the main factors affecting the choice of portfolio and whether the determinants of environmental resource extraction differ between the groups. Other papers have paid specific attention to the role of the environmental income component in household wealth (Angelsen and Dokken, 2018; Angelsen et al., 2014).

We contribute to these studies in three ways. First and foremost, the studies used the livelihood strategies as a static characterisation of smallholders. We bring a new perspective by identifying how portfolios are built in villages with different poverty levels and how they could be developed to alleviate poverty. Second, we focus on the elasticity of poverty with respect to portfolios rather than analysing mean differences in wealth or income. This is crucial as income growth can have ambiguous effects on poverty depending on where in the income distribution the growth occurs. Third, by extending the theory developed by Ibragimov and Müller (2010) to regression analysis, we derive estimates across geographical areas and make robust inferences about population-level effects.

In the operations management literature, rural poverty alleviation is rapidly gaining attention being one of the necessary conditions for responsible sourcing. This stream of research is however still a relatively nascent research area (Atasu et al., 2020; Plambeck and Kamalini, 2020). Voors et al. (2018) looked at the extent of elite capture of development aid in rural villages in Sierra Leone. The authors found little evidence that project resources are captured by the local elite, but are often better managed under decentralised governance systems. Thus, the authors focus on project management, rather than project selection, and the interplay with different governance modalities. Our research is also related to the literature on agricultural operations, though these studies focus in particular on the composition of the farming portfolio of rural smallholders. Federgruen et al. (2019) analysed the project selection decisions of smallholder farming portfolios in a supply chain context, namely via contract farming. Smallholder farmers can select a contract, for a guaranteed price, from a menu offered by a manufacturer in advance of the growing season and manage their farming activities accordingly. Contract farming has also been shown to improve welfare when short-sighted behaviour causes frequent overproduction or underproduction of agricultural products (Hu et al., 2019). Levi et al. (2020) studied the impact of online agricultural platforms on modal prices and rural smallholders' welfare and demonstrated that the rate of improvement depends on the commodity smallholders provide. Liao et al. (2019) also study farmer welfare in the context of commodity markets and show when maximising total welfare is achieved by providing price information to farmers for making informed decisions regarding which crop to grow. A study placed more at the interface at natural resources and farming income was conducted by De Zegher et al. (2018), who found that smallholder livelihoods can be improved and deforestation reduced if buyers eliminate payment delay for the farmers' produce, but only for those in villages where no illegal deforestation occurred.

As more companies and social enterprises seek to attain social goals by directly sourcing from poor smallholders in developing countries (Sodhi and Tang, 2011, 2014; Tang, 2018), a better understanding of how portfolios bear on poverty will be essential. Traditionally, the focus has lied on farming income, whereas smallholders are shown to have a wide range of production activities (whether for own use or for conversion to cash income). We therefore wish to expand the horizon beyond poverty alleviation focused on operational levers impacting income from farming practices alone. Rather, we hope to shed more light on the ability of households to develop patterns of value-creating actions in selecting their complete livelihood portfolio.

In empirical OM settings, establishing what types of portfolios are or should be pursued can be a challenge, especially when many configurations are possible. As in the livelihoods literature in economics, this has been typically overcome through clustering analysis. Masini and Van Wassenhove (2009) use a multi-tiered cluster analysis (Ward and K-means) to identify groups of firms that have similar enterprise resource planning (ERP) needs and find that the configurational analysis offers insights explaining firm performance differences. Vrecko and Langer (2013), using K-means, found that investors can be clustered into distinct subgroups via their customisation patterns of their investment portfolios. Eccles et al. (2014) use clustering to group firms by their adoption (or lack of adoption) of different types of sustainability policies (environmental or social). For a complete review of clustering in OM, we refer to Brusco et al. (2017).

4.3 Data description

For our livelihood analysis, we use CIFOR's Poverty and Environment (PEN) global data set. This is the largest quantitative, global-comparative research project on forests and rural livelihoods to date. PEN used a standardised set questionnaires to collect household-level socio-economic and village-level contextual data from a diverse sample of smallholder households, i.e., households that operate under a small-scale agricultural model. In the PEN research, a village is defined as the lowest administrative unit in an area and is typically under the jurisdiction of a village leader/council. A household is defined as a group of people (normally family members) living under the same roof, and pooling resources (labour and income).

Though the data is cross-sectional, this unified data collection method enables comparison of results across study areas, a property that country level data sets on poverty currently lack. The study sites were selected to be representative of smallholder-dominated (sub)tropical regions (Latin America, Asia, and Sub-Saharan Africa) with moderate-to-good access to forest resources. While PEN sites and villages were selected according to explicit stratification criteria, the within-village selection of households followed random sampling. Four quarterly surveys collected data on assets, income, and production cost from seven major income sources: forest and non-forest environmental income, cropping, livestock, wage employment, business, and other income including pensions and remittances. The survey has been used extensively in the environmental economics literature (e.g. Angelsen and Dokken (2018), Duchelle et al. (2014), Watmough et al. (2016)). Detailed information on the data collection process can be found in Angelsen et al. (2014).

The full data set contains survey data from 7978 households across 333 villages. Since we are interested in village poverty, we restrict the sample to villages where 30 or more households were selected for the questionnaire. Further, we exclude 3 households that have no income or a livelihood portfolio and the households that have no data on available forest land or agricultural land, which are used as control variables. Last, since this process left only 2 villages in Latin America, we restrict our analysis to Africa and Asia. Though this means results cannot be generalized to Latin-America, since over 90% of the rural poor live in Africa and Asia, we believe the impact of our study remains. This process leaves 4,180 rural smallholders living in 81 different villages across 16 developing countries.

Income is defined as the value added of labour and capital minus the cost. For agriculture and extractive activities, this means the gross value (quantity produced multiplied by price) minus the costs of purchased inputs (e.g., fertilizers, seeds, tools, hired labor, etc). In line with previous literature, both the household's subsistence extraction and the production that generates cash income are considered. It therefore includes the value of marketed as well as non-marketed goods. The value of non-marketed goods was established using local market prices. For inter-household comparison, income and assets are adjusted for adult equivalent units (AEU) and purchasing power party (PPP) rates. Thus, income and assets are reported as PPP adjusted USD per AEU.

Total household income is derived from a combination of 7 income sources that in turn originate from 3 broad categories: environment, farm, and off-farm. Environmnental income is derived from forest or non-forest sources. Income is considered from forests if that income depends on the existence of forest cover. Wood products, fish from rivers inside forests, and payments for ecosystem services are classified as forest income. Mineral extraction and natural products caught or harvested outside of forests are classified as non-forest environmental income. Natural resources are typically used for a number of different applications. In the PEN dataset, wood fuels (firewood, charcoal, etc) are the dominant category of forest income ($\sim 35\%$), after which comes food, which can be fish, bushmeat, fruits, mushrooms, etc ($\sim 30\%$). The third largest category is structural and fibre products such as poles, sawn wood, leaves, grass, etc ($\sim 25\%$). The usage of non-forest environmental income is slightly different, with food as the dominant category ($\sim 50\%$), followed by fuel ($\sim 20\%$) (Angelsen et al., 2014).

We differentiate farm income between cropping and livestock income. Crop income comes from cropping on agricultural or agroforestry land. Livestock income consists of the consumption or sale of animal products and services (e.g. renting out horsepower). Lastly, off-farm income consists of wage income from employed labour, income from self-owned businesses, and other income. The latter is derived from remittances, pensions, gifts, and any other sources not captured by the previous categories. Self-owned businesses can encompass offering specific services, but also selling arts and crafts. These may be obtained from forest products, in which case the raw material (e.g. timber) is considered income from forest resources and the added value (e.g. sculpting the timber) is considered income from self-owned businesses.

We present the summary statistics of absolute income levels and the average reliance on these income sources across villages in Table 4.1. We can see that each income category (Environment, Farm, and Off-farm) contributes over 20% to total income and though absolute income differs across the two continents, the relative contribution of income sources varies to a lesser extent.

We use a number of control variables in our analysis. Country dummies capture any country specific effects and in addition we control for some village characteristics. Existing research in development economics has greatly contributed to our understanding of poverty. Studies have proved the importance of both income growth and redistribution to alleviate poverty (e.g. Bluhm et al. (2018); Kalwij and Verschoor (2007)). Thus, we include village-level mean income and inequality (measured by the Gini coefficient) in

Table 4.1 Village summary statistics: mean absolute and relative income

Income category		Global		Africa		Asia	
		Absolute	Relative	Absolute	Relative	Absolute	Relative
Environment	Forest	262.58 (31.65)	19.96 (1.32)	214.03 (56.62)	18.70 (2.12)	305.48 (31.70)	21.07 (1.64)
	Non-forest	85.51 (14.14)	8.34 (0.80)	114.30 (27.92)	12.43 (1.26)	60.08 (8.81)	4.72 (0.63)
Farm	Cropping	327.88 (30.72)	29.18 (1.47)	242.49 (29.90)	31.58 (1.86)	403.34 (49.01)	27.07 (2.20)
	Livestock	200.78 (21.19)	14.54 (1.11)	118.64 (23.75)	13.30 (1.85)	273.36 (30.08)	15.63 (1.31)
Off-farm	Wage	156.97 (17.03)	13.66 (1.18)	91.50 (20.06)	10.00 (1.45)	214.82 (23.60)	16.90 (1.68)
	Business	171.59 (35.34)	7.97 (0.85)	138.80 (48.83)	9.22 (1.29)	200.57 (50.82)	6.87 (1.11)
	Other	82.14 (15.69)	6.34 (0.75)	41.16 (8.16)	4.76 (0.46)	118.35 (27.66)	7.74 (1.33)
Total		1287.44 (97.06)	100	960.92 (159.31)	100	1576.00 (99.10)	100
	Villages	81		38		43	
	Households	4180		2171		2009	

Note: The data set contains income data on seven income components within three broad-level categories (Environment, Farm, Off-farm). Values are household averages across villages with the standard error of the mean in parentheses. Absolute incomes are adjusted for USD Purchasing Power Parity and converted to Adult Equivalent Units.

our analysis which will allow us to assess the effect of income composition on poverty above and beyond income growth and distribution.

Second, we control for some land characteristics in villages being a key productive asset and a potentially important determinant of both poverty and cluster membership. In terms of tenure, land is typically categorized in three ownership categories: community-, state- or privately owned land where private ownership can be by the villagers themselves or other outside parties (corporations, large-scale farmers). People tend to manage resources more sustainably on communal lands than on for instance state-owned land, especially when enforcement is lacking (FAO and UNEP, 2020; Jagger et al., 2014). Moreover, the tenure regime influences whether the land can be used based on what is needed from a community perspective, which can be more troublesome with state- and privately-owned land. On the other hand, state- and privately-owned land are often in better shape (less degraded) and encompass larger areas. Note that the degradation is not necessarily caused by the tenure regime: the process of devolving rights from states to communities frequently targets low-value and degraded lands (Jagger et al., 2014). The tenure regime can therefore interact with village poverty as well as the relative attractiveness of certain portfolios.

Smallholders can privately own land, which is mostly agricultural land, but can also be forest land. A smallholder with forest land can often convert it to pasture or cropland but chooses not to (e.g., he wants to use it for forest products, does not have the resources to cultivate more land, etc). Private forest lands are usually much closer to homesteads than community- and state-owned forest lands and therefore preferred for the collection of regularly used subsistence products. We thus control for the average amount of forest land owned by the sampled smallholders in each village as some initial endowment.[1] In addition, we control for the interaction between the share of community land and privately owned forest land. A higher share of community land could give the community more flexibility to keep some land as forest or could be disadvantageous when it is overexploited, but either effect may be less important if the members of that community own a sufficient amount of forest land themselves.

4.4 Model set-up

We first outline the main community-level variables: poverty, mean income, and inequality. The two poverty constructs (headcount and gap) are the dependent variables of our model whereas inequality and mean income are part of the set of explanatory variables. Then, we discuss the approach for obtaining smallholders' income compositions and the village-level configurations of those compositions. Last, we present the estimation framework which incorporates all the elements.

We predict poverty using the Foster-Greer-Thorbecke (FGT) index as the dependent variable. Specifically, we consider the poverty headcount and poverty gap index. The headcount index measures the proportion of people with an income y that fall below the poverty line l ($H = Pr\{y \leq l\}$). This is the most widely used measure in literature and policy setting. However, it does not indicate the extent to which individuals fall below that poverty line. This is obtained by the poverty gap index ($G = \frac{l-y}{l} \times Pr\{y \leq l\}$). We thus define our poverty measures as

[1] We also controlled for the average amount of agricultural land, but this was not significant.

$$P_i = \frac{1}{n_i} \sum_{j=1}^{n_i} \left(\frac{l_i - y_{ij}}{l_i} \right)_+^\alpha \tag{4.1}$$

where y_{ij} is the total income of an individual smallholder household drawn randomly from village i; n_i the total number of smallholders in that village, and $x_+ = \max(x, 0)$, which means that the difference is zero for those households with an income above the poverty line. We obtain the headcount and poverty gap index for $\alpha = 0$ and $\alpha = 1$ respectively and thus let $P_i \in \{H_i, G_i\}$. The poverty line l is typically 2/3 of median income. Since there is a considerable difference between countries, between urban and rural incomes, and even between (sub)tropical and other regions, these poverty lines are constructed at village level. Moreover, existing country-level poverty lines would overestimate poverty for our data since these typically only measure cash income and exclude environmental sources.

The Gini coefficient is used to incorporate the effect of distributional changes in income on poverty. For a random village i with households' incomes y_h, $h = 1$ to n_i, that are indexed in non-decreasing order ($y_{h-1} \leq y_h$), the inequality statistic is defined as

$$I_i = 1 - \frac{1}{n_i} \sum_{h=1}^{n_i} (y_h + y_{h-1}) \tag{4.2}$$

In the next section we outline the definition of livelihood portfolios that we use to understand their effect on rural poverty and the approach to introducing them in the poverty analyses.

4.4.1 Income Composition

Total income of rural smallholder households is composed of a range of different sources. Suppose each household pursues a combination of sources $q = 1, 2, ..., Q$ and derives an income from each of those sources worth w_q. These sources are mutually exclusive and add up to a household's total income, or $y = w_1 + .. + w_Q$. As such, $\omega = \left[\frac{w_1}{y}, .., \frac{w_Q}{y}\right]$ would be the compositional vector of a household's income derivation pattern and this pattern will change across smallholders. Since an infinite number of different combinations is possible, we use K-means clustering to find the common livelihood compositions of the smallholders in our data set, i.e., we cluster on vector ω. Clustering and component extraction techniques are frequently used in livelihood analyses (Martin and Lorenzen, 2016; Nguyen et al., 2015) as well as in portfolio selection problems

(Vrecko and Langer, 2013) to uncover common configurations within a broad set of possibilities. The approach for deriving these clusters is discussed in the next section.

Different clusters combine income sources in different proportions and amount to different livelihood portfolios in villages. As such, we introduce cluster proportions as explanatory variables in our model to determine the responsiveness of village level poverty to the variation in the proportion of households in a specific income cluster. We calculate the village-level proportions of smallholder cluster membership as

$$\boldsymbol{\pi}_i = \left[\frac{n_{i1}}{n_i}, .., \frac{n_{iK}}{n_i}\right] \quad i = 1, .., N, \;\; k = 1, .., K \tag{4.3}$$

with N villages and K clusters, we define $\mathbf{\Pi}$ as the $N \times K$ matrix with the compositional vector for each village. Element $\mathbf{\Pi}_{ik}$ is the proportion constituted by the number of households in cluster k (n_{ik}) relative to the total number of households in that village (n_i). We will refer to this in the rest of the paper as the cluster proportion or cluster membership proportions.

Alternatively, we could assess the average proportion of income that smallholders derive from each source in the village as the explanatory variable, which would be represented by the village average of vector ω. This would provide an initial insight into how a greater reliance on a specific income source affects poverty. However, smallholders rarely pursue a single income source, but rather make combinations to achieve a diversified portfolio. We find that the village-level income proportions and village-level cluster proportions are highly correlated with each other (see Appendix). These parallel approaches to analysing the issue provide consistent evidence which, given the high correlation, was expected. Nonetheless, the greater extent of variation in the cluster proportions helps pin down the effects of changes in this aspect of livelihood portfolios on poverty more precisely. Using the ensemble of portfolio measures that generates the most reliable and precise set of estimates is important for drawing accurate conclusions about portfolio effects on poverty. As such, analysing and interpreting the effect of different combinations of livelihoods on poverty (using cluster analysis) is more appropriate in this context.

Before introducing our model specification, we will first discuss our clustering approach, stability assessments, and the cluster characterisations.

Cluster Validity

K-means clustering is an unsupervised learning method that starts the grouping process with K number of centroids or starting seeds, which are randomly selected observations. Each of the remaining observations is assigned to the centroid that minimises the chosen distance measure between the observation and cluster mean. After all are assigned, the new mean value of each cluster is calculated and every observation is checked to see if within-cluster variation can be reduced by reassigning it to a different grouping. This variance minimisation technique is an iterative process until convergence is achieved and the observations are organised into a set of K clusters.[2]

One of the key decision variables for clustering is the determination of the number of clusters or centroids, K. We use the following formal methods and informal approaches to select K and subsequently assess the stability of the clusters. First, we run the K-means MacQueen algorithm with 3 to 13 starting seeds. This technique assigns (and reassigns) observations based on the Euclidean distance between the coordinate and the centroid, which is the mean of the 'belonging' cases (MacQueen et al., 1967).[3] A clear natural hierarchy emerges in the clusters: a cluster is added by splitting another while the rest remains relatively stable (see Figure 4.4 in the Appendix). The number of centroids is selected via several approaches. First, we use the selection method employed by (Baudry et al., 2012), which is based on the slope heuristics that minimises a nonasymptotic penalty criterion and is recommended by Godichon-Baggioni et al. (2019) for the clustering of compositional data. The method suggests 7 clusters for our data. To further verify the internal validity of using 7 centroids, we also look at the average Silhouette Width, which compares the tightness (average within-cluster dissimilarity) and separation (average between cluster dissimilarity) of clusters (Rousseeuw, 1987). A high silhouette score means that the within dissimilarity is small compared to the smallest between dissimilarity, implying that the observation is 'well-clustered'. Though this method is not specifically adapted to compositional data, it also suggests that 7 centroids are most appropriate.[4] The figure illustrating the silhouette width can be found in the Appendix.

Seven centroids are also theoretically meaningful, ensuring greater validity of the groups and of their interpretation, for the following reasons. First, we have seven income

[2]Note that because the variables are measured in the same units and on the same scale (percentages) there is no need to standardise them as is usually required in clustering.

[3]To ensure the validity of this algorithm, we also use the K-means algorithm by Hartigan and Wong (1979), which reassigns points based on the within cluster sum of squares, and find that fewer than 5 households are grouped differently.

[4]Since the elements on which we cluster are linear dependent due to the compositional nature of the data, we must note that not all validity assessment techniques are appropriate (i.e. those that assess stability by removing a column or that are based on the correlation matrix).

sources on which we cluster and, as we will see, with seven centroids each income source represents the highest average proportion in a cluster. We refer to this as the primary livelihood strategy of the cluster (though it may not be the primary strategy for each smallholder in that group, it is on average across smallholders). Second, with 7 clusters, the minimum proportion of this ‘primary’ strategy is strictly larger than 0 for each smallholder in that group. Since this is not true for all clusters with $K = 6$, it points to the fact that there are some smallholders in these groups for which the specification can be improved. Tables and figures related to the centroid selection can be found in the Appendix.

Cluster Stability

Cluster stability is measured as the amount of variation in the clustering solution. First, the stability of the clusters can be affected by the K-means method as the results are realised from just one set of seed points and thus may achieve only a local optimum. We ensure the global optimality of the solution by performing 5,000 runs with different sets of randomly drawn initial seed values, per the suggestion of Brusco et al. (2017). Running multiple restarts only results in the re-allocation of a handful of households. Thus, the clustering process is consistent and stable in the sense that only a few different partitions are found across a broad spectrum of starting solutions.

Secondly, the clusters are considered stable if the solution does not vary much over different samples drawn from the input data (Jain, 2010). We use the Jaccard coefficient as a measure of cluster stability, which is a similarity measure between matched clusters resulting from different samples drawn from the data. One of the advantages of this approach is that we can assess cluster-wise stability. Instead of having an overall stability measure, having a coefficient for each cluster shows to what extent the clustering process finds meaningful and stable patterns in the data, as well as whether this applies to some but not all of the clusters. The stability is assessed by the (non-parametric) bootstrap distribution of the Jaccard coefficient and every single cluster is compared to the most similar cluster in the bootstrapped data sets. The bootstrap introduces some bias and variation, because in reality no true underlying distribution and no true clustering is known. We run 100 re-sampling runs and find that the mean of the Jaccard coefficent is higher than 0.75 for each of the 7 clusters. Note that over 0.6 indicates a pattern, whereas valid and stable clusters yield values of 0.75 or more (Hennig, 2007). We arrive to the same conclusion when we use subsetting as an alternative resampling method. We set the size of the subsets at 2,090 observations, which constitutes 1/2 of our data. Using 100 reruns, we calculate the mean of the

Jaccard coefficient and find that 6 clusters score above 0.75, and the second cluster only slightly below. The results are reported in Table 4.2.

Table 4.2 Jaccard coefficients of cluster resampling

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Bootstrap	0.950	0.761	0.883	0.910	0.910	0.923	0.891
Subsetting	0.944	0.715	0.857	0.902	0.918	0.924	0.902

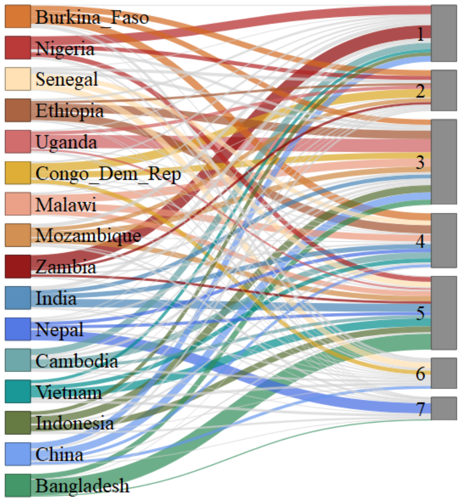
Note: The mean of the Jaccard similarity index is reported over 100 reruns of either a non-parametric bootstrap or resampling by subsetting. If patterns exist, the coefficient yields at least 0.6; highly stable clusters typically yield 0.75.

Thirdly, we want to ensure that our results can be robustly interpreted using this clustering process. This means that the clusters should be representative of the group we analyze (smallholders in the (sub)tropics with moderate-to-good access to forest resources). We already found with the re-runs and bootstrapping that within our sample, the clustering results are highly stable. However, as you may recall, the clustering solution was derived from a subset of the complete sample as we selected households from villages where more than 30 surveys were conducted. We therefore perform the same K-means algorithm on the complete sample of 7,696 households. We match the clusters from the full sample with the clusters from the subsample based on the values of their centroids. The matching falls out in a straightforward way as the patterns and centroids are very close. We find that on average only 2% of the households from the subsample are allocated to a different group when clustering the complete sample, which attests to the stability of the clusters out of sample and builds trust in the ability to generalise our findings.

Since we analyze livelihood patterns in a number of different countries, we also assess how well represented the countries are in the clusters, or whether, for example, some livelihood patterns are specific to a country. Figure 4.1 shows the diversity with which the countries map to the seven clusters, with the three most sizable flows of each country colored in. The Herfindahl-Hirschmann concentration index and Shannon's entropy measure show more formally that clusters are populated by a broad range of countries. In terms of the HHI, only cluster 7 is relatively concentrated having a significant presence of Nepal although this representation does not lead the cluster to score low on Shannon's entropy.

Lastly, we must recognise the structure of the data we are clustering. Our compositional data is made up of Q proportions and the sample space of compositional data is the simplex, which we refer to as $\mathbb{S}^Q$. For the clustering, one can consider adopting the Aitchinson distance measure, which highlights the relative difference between composi-

Fig. 4.1 Cluster Concentration



	HHI^{-1}	Shannon
Cluster 1	0.865	0.505
Cluster 2	0.860	0.483
Cluster 3	0.896	0.436
Cluster 4	0.856	0.492
Cluster 5	0.897	0.465
Cluster 6	0.899	0.441
Cluster 7	0.653	0.554

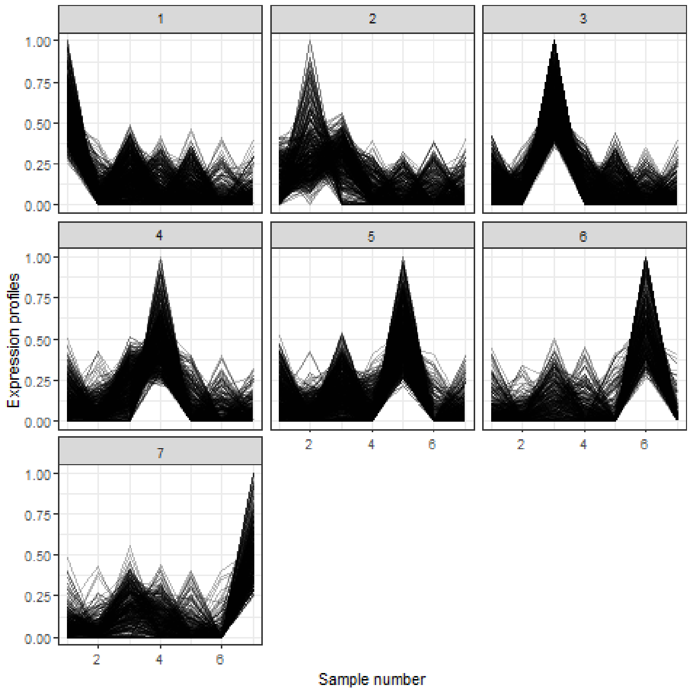
Note: The Sankey diagram shows the relative number of households from each country allocated to the 7 clusters. The three largest flows from each country are colored in. The table reports the inverse Herfindahl-Hirschmann concentration index and Shannon's entropy measure of each of the clusters. The indices are bound between 0 and 1 and take on a value of 0 when the cluster is only present in a single country.

tions on the simplex, instead of the Euclidean distance, which is based on absolute differences between compositional vectors. However, the Aitchinson transformation breaks down when compositions contain a zero value since relative distances cannot be calculated. Zero replacement techniques have been found to cause incorrect clustering because the distance of a composition with values tending to zero from others, will tend toward infinity. The use of these techniques can therefore cause algorithms to group together profiles with several (near) zeros in common rather than those with a strong non-zero coordinate in common (Godichon-Baggioni et al., 2019). To assess stability of the clusters for this relative distance measure, we subset our data to be populated exclusively by households that have positive contributions from each income component, limiting the sample space to the reduced simplex. Despite being just below 20% of our original sample (833 versus 4,180 households), the clusters in the reduced set follow the same patterns and characterisation as our main sample, regardless of distance measure. Even household level outcomes within the reduced set only vary slightly between the Euclidean and Aitchinson distance measures. For instance, matching the clusters based on their centroids shows that 87.4% of the households are allocated to the same group when using the different distance measures. We therefore conclude that we can safely use the Euclidean distance for our sample set.

Cluster Characterisation

The cluster profiles are illustrated in Figure 4.2 and the corresponding cluster means, or cluster centers, are reported in Table 4.4. We can see that the algorithm produces clusters in which one of the 7 income sources is the main contributor to income, on average, and that main contributor tends to be complemented with a relatively large secondary and often tertiary source of income to form a portfolio. The secondary source and tertiary sources are typically cropping income and forest income.

Fig. 4.2 Cluster Profiles



Note: The 7 income components are plotted on the x-axis (forest, non-forest, cropping, livestock, wage, business, and other) and the household allocation profiles are plotted on the y-axis.

Table 4.3 Cluster Characterisation

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Primary	Forest	Non-forest	Crop	Livestock	Wage	Business	Other
Secondaries	Crop/Wage	Crop/Forest	Forest/Livestock	Crop/Forest	Crop/Forest	Crop/Forest	Crop/Livestock

In Table 4.4 we can see that the 3 income sources with the highest average proportions in the clusters make up around 80% of total income. In the rest of the paper we will refer to the cluster either by the three major income sources characterisations or for convenience by their primary source.

Table 4.4 Cluster Means (%)

Income category		Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Environment	Forest	54.77	14.67	11.53	12.51	14.01	8.61	7.87
		(0.56)	(0.51)	(0.32)	(0.41)	(0.42)	(0.53)	(0.40)
	Non-forest	5.78	30.74	6.67	5.61	4.52	4.76	4.84
		(0.27)	(0.81)	(0.23)	(0.28)	(0.22)	(0.35)	(0.31)
Farm	Cropping	17.40	28.08	60.98	20.69	18.70	13.79	18.50
		(0.44)	(0.59)	(0.50)	(0.51)	(0.47)	(0.67)	(0.60)
	Livestock	7.25	7.82	7.93	48.17	5.68	7.82	11.13
		(0.35)	(0.39)	(0.30)	(0.63)	(0.29)	(0.55)	(0.50)
Off-farm	Wage	8.44	6.43	6.39	5.93	50.26	4.85	4.90
		(0.37)	(0.39)	(0.31)	(0.37)	(0.61)	(0.51)	(0.42)
	Business	2.65	6.33	2.92	3.51	2.12	56.48	2.18
		(0.24)	(0.42)	(0.20)	(0.29)	(0.22)	(1.05)	(0.29)
	Other	3.71	5.93	3.59	3.58	4.71	3.70	50.58
		(0.23)	(0.36)	(0.20)	(0.24)	(0.28)	(0.38)	(0.86)
Observations		716	490	932	593	748	318	383

Note: Cluster means are reported as percentages and the standard error of the mean is reported in brackets.

4.4.2 Compositional Data Construction

In our poverty analysis, the variables of interest are compositional data: the proportions of smallholders in cluster k. These vectors are a closed number systems and therefore subject to a non-negativity and a constant sum constraint:

$$\left\{ \boldsymbol{\pi}_i \in \mathbb{S}^K \mid \boldsymbol{\Pi}_{ik} \geq 0, \ \sum_{k=1}^{K} \boldsymbol{\Pi}_{ik} = 1 \quad i = 1, .., N, \ \ k = 1, .., K \right\}$$

where $\boldsymbol{\pi}_i$ characterises the vector of cluster proportions of village i and $\boldsymbol{\Pi}$ the matrix of all villages' cluster proportions. The unit simplex is a $K-1$ dimensional space embedded in a K dimensional real space. Traditional multivariate analysis and the interpretation of coefficients are complicated because compositional data is mapped to the unit simplex. We must therefore transform the data from the unit simplex to real Euclidean space prior to applying multivariate statistical techniques.

Regression specifications with predictor variables that sum to unity suffer from multicollinearity, which is typically overcome by eliminating one variable to function as the base group. A composition $\Pi_i 1, ..., \Pi_i K$ can be completely specified by the components of a $K-1$ subvector. Reparametrisation using the log transformation captures the non-linearities and removes the non-negativity constraint. This also results in an interpretation of the coefficients as elasticities. Thus, the transformed cluster proportion vector would be $\ln(\boldsymbol{\Pi_{i1}}, .., \boldsymbol{\Pi_{iK-1}})$.

Despite being one of the more popular solutions in economic applications, it has been shown that the shares from this model are not correctly bounded to the unit simplex and subject to an inconsistency (Pawlowsky-Glahn and Buccianti, 2011). The essential consequence of the unit sum constraint is that changes in one component are not invariant to changes in other components and standard statistical techniques that are devised for unconstrained random variables and that use the covariance or correlation matrix of vectors of observations cannot be used for the compositional data in its raw form (Aitchison, 1982; Buccianti et al., 2006).[5] Moreover, compositional data are non-normally distributed - since they must always lie between zero and one and must sum to one. Therefore, with the income patterns as the variables of interest, we cannot ignore the compositional nature of the data if we wish to make robust inferences.

In our approach, we map the composition to real Euclidean space by using the additive logratio (alr) transformation, originally developed by Aitchison (1982). This approach takes the log of a vector of compositional ratios rather than the raw proportions. Specifically, for the analysis we will work with the vector $\ln\left(\frac{\mathbf{\Pi}_{i1}}{\mathbf{\Pi}_{iB}}, ..., \frac{\mathbf{\Pi}_{iK-1}}{\mathbf{\Pi}_{iB}}\right)$. Note that by inputting the values from Equation 4.3, the denominator (total number of villagers) cancels out and this vector can be simply interpreted as the proportions of cluster frequencies: $\ln\left(\frac{n_{i1}}{n_{iB}}, ..., \frac{n_{iK-1}}{n_{iB}}\right)$. In other words, the logratio of the cluster proportions is the same as the logratio of the cluster frequencies. Since we have $K = 7$ clusters, we work with $N \times 6$ dimensions. Subscript B denotes the base category.

For our data, we select the cropping category as the base. Over 95% of the smallholders in our data set derive some of their income from cropping and in all of the villages there are smallholders with cropping income, so this source can be seen as the most accessible. The cropping cluster is also the largest group of smallholders with members in all but 8 villages.

The advantage of the additive logratio is that it retains parameter interpretations as well as the logical consistency argument that shares are restricted to the unit simplex. The technique removes the restrictions and transforms compositional data onto a scale where they follow a multivariate normal distribution.

Special care must be taken in these transformations since income data with disaggregate categories often yields 0 values (i.e. when a village has no members in a particular cluster portfolio). A logarithmic transformation would then exclude villages with at

[5]Note that this includes principal component analysis and factor analysis, but excludes clustering techniques based on geometrical separation.

least one cluster membership of 0, which is the major drawback of compositional data analysis. One instance where the transformation fails is when there are no smallholders in the base group. This event is fortunately rare. There are only 8 villages for which the cluster proportion of cropping is zero, but we can handle these using zero replacement. Zero replacement techniques are a common approach in count data when the zero observation can be rationalised as an artefact of the sampling process (Pawlowsky-Glahn and Buccianti, 2011), i.e., if it is likely that that component is represented in the population, but by coincidence or due to limited sample size, not in the sample. Over 95% of smallholders in our sample have cropping income, so even in the villages where no households belong to the cropping cluster, households derive income from cropping. In fact, there are households that derive over 30% of their income from cropping in these 8 villages. We therefore argue that it is highly likely that a slightly larger or different sample would have allocated at least one smallholder to the cropping cluster in the villages where none were counted.

We use the Bayesian-multiplicative technique to treat the zeros of the base group B, which replaces zero values from compositional count data by its posterior Bayesian estimate. Importantly, the modification does not distort the covariance structure since it modifies the nonzero parts in a multiplicative way to preserve the original ratios between the elements as well as the total sum representation of the vector (Martín-Fernández et al., 2015). We use the well-known Bayes-Laplace prior by applying the expression

$$b\mathbf{\Pi}_{ik} = \begin{cases} \mathbf{\Pi}_{ik} & \text{if } \mathbf{\Pi}_{iB} > 0 \\ \frac{1}{n_i+v_i} & \text{if } \mathbf{\Pi}_{iB} = 0 \text{ and } k = B \\ \mathbf{\Pi}_{ik}(1 - \frac{1}{n_i+v_i}) & \text{if } \mathbf{\Pi}_{iB} = 0 \text{ and } k \neq B \end{cases} \tag{4.4}$$

where n_i is the total count of the vector, i.e. number of smallholders in village i, and v_i is the number of non-zero values in the vector plus the base group, i.e. the number of elements that will be modified. We find that one village is an influential outlier, exacerbated by the subsequent logarithmic transformation, and remove it from the data set.[6]

[6] We take a simple example to illustrate the transformation. A village with a positive proportion of smallholders in all but the cropping cluster, has $v_i = 7$. The cropping cluster will be increased by the amount in the second term. To preserve the ratios and unit sum, the other positive components will be reduced to the amount given by the third term.

To economise on notation, going forward we denote the logratio vectors of the cluster proportions of village i by $\mathbf{z}_i$:

$$\mathbf{z}_i \in \left\{ \left[\frac{b\mathbf{\Pi}_{i1}}{b\mathbf{\Pi}_{iB}}, ..., \frac{b\mathbf{\Pi}_{iK-1}}{b\mathbf{\Pi}_{iB}} \right] \right\} \tag{4.5}$$

and we denote $\mathbf{Z}$ as the $N \times r$ matrix of the cluster proportion logratios for N villages and $r = 6$ logratios.

Villages can also face zeros in the income and cluster proportions other than the base group. Replacement techniques may not be appropriate in these cases since it is more difficult to rationalise that these zeros are not part of the data generating process. As mentioned, cropping is pursued by almost all smallholders, but this cannot be said for all the other income sources. It is therefore not obvious that if we, for example, took a larger or slightly different sample of a village that currently has zero values, we would find that all income sources are pursued and that each cluster is populated. These zero observations must then be classified as essential zeros and should not be replaced. To address essential zeros, we use the method proposed by Battese (1997) for our estimation, which was applied in an agricultural setting in Battese et al. (1996). The author introduces a form of conditional modelling that separates out the zeros. Using dummy variables that represent the occurrence of zero values, the effect on poverty can be decomposed into two components according to the value of Z as defined in condition (4.5):

$$(\mathbf{z}_i > 0)\ln(\mathbf{z}_i)\beta_{\mathbf{z}_i>0} + (\mathbf{z}_i = 0)\beta_{\mathbf{z}_i=0} \tag{4.6}$$

The combination of the additive logratio, the Bayesian-multiplication, and the Battese zero value techniques allows us to estimate efficient and unbiased portfolio estimators with OLS using the full data set of compositional data.

4.4.3 Estimation Framework

The headcount and poverty gap ratio, defined in Equation (4.1), is typically characterised in terms of the poverty line, the mean income of the distribution, and a variable that approaches the Lorenz curve (which describes the income distribution). As a result, changes in aggregate poverty for a given poverty line are often decomposed in terms of the effect on poverty due to a change in aggregate income while holding distribution constant and the effect on poverty due to a change in the income distribution while keeping mean income constant (Bluhm et al., 2018; Datt and Ravallion, 1992; Kalwij and Verschoor, 2007). However, an error term remains due to higher moments that cannot perfectly be captured without making assumptions about the underlying distribution of incomes (Datt and Ravallion, 1992).

The concerns of the studies that contributed to the dynamics of poverty was solely with how the mean income and inequality of income in the aggregate contributed to poverty. If income portfolios matter in determining poverty, the observational models focusing on aggregate determinants have an omitted variables problem and the next step would be to bring the effects of income portfolios on poverty into the systematic part of the observational model and out of the error term. Our observational model explores the role of income composition in determining poverty by introducing compositional variables into the regression model with the aim of identifying the effects of income portfolios, controlling for mean income and inequality.

We specify the following observational model to obtain composition elasticities using the logratios of the cluster proportions ($b\mathbf{\Pi}$) as covariates to derive composition elasticities:

$$\ln P_i = \alpha + \gamma_1 \ln \mu_i + \gamma_2 \ln I_i + \sum_{r=1}^{6} \beta_r \ln \mathbf{Z}_{ir} + u_i \tag{4.7}$$

Recall that P stands for the poverty measure, which can be the headcount ratio H or poverty gap measure G as defined in Equation (4.1), the mean income μ is estimated by sample mean $\overline{y}$, inequality measure I is estimated using $\hat{I}$ operationalised through the Gini coefficient, and $\mathbf{Z}_r$ are the six logratios of the cluster frequencies.

Our final specification also includes the Battese dummy variables to carry out the estimation with zero values, and contains control variables that capture differences in compositions between villages that can confound their relation with poverty. We also include dummies for each country to absorb any country-level effects. Thus, our complete estimation takes the form of:

$$\ln P_i = \hat{\alpha} + \hat{\gamma}_1 \ln \overline{y}_i + \hat{\gamma}_2 \ln \hat{I}_i + \sum_{r=1}^{6} (\hat{\eta}_r D_{ir} + \hat{\beta}_r \ln \mathbf{Z}^*_{ir}) + \text{controls} + v_i \tag{4.8}$$

where $D_{ir} = 1$ if $\mathbf{Z}_{ir} = 0$, $D_{ir} = 0$ if $\mathbf{Z}_{ir} > 0$, and $\mathbf{Z}^*_{ir} = \max\{\mathbf{Z}_{ir}, D_{ir}\}$ for village i and logratio r. Thus, when $\mathbf{Z}_{ir}$ has a positive value, $\ln \mathbf{Z}^*_{ir} = \ln \mathbf{Z}_{ir}$ and when $\mathbf{Z}_{ir} = 0$, $\ln \mathbf{Z}^*_{ir} = 0$. Per condition (4.6), the estimator $\hat{\beta}_r$ represents the effect of a change in the logratio r on poverty for $\mathbf{Z}_{ir} > 0$, with intercept $\hat{\alpha}$. When $D_{ir} = 1$, the second effect of condition (4.6), which equals $(\mathbf{Z}_{ir} = 0)\beta_{\mathbf{Z}_{ir}=0}$, is absorbed by the constant as $\hat{\alpha} + \hat{\eta}_r$. Thus, $\hat{\alpha}$ represents the common intercept of the villages that are in the open simplex, i.e. the intercept of villages for whom all $\mathbf{Z}_{ir}$'s are positive. On the other hand, if all the $\mathbf{Z}_{ir}$'s are zero, the constant would be $\hat{\alpha}$ plus the coefficients of the dummies. In practice, this means that every smallholder in a village is member of the cropping cluster. Note that this event does not occur in our data set.

Before moving to our analysis, we derive the elasticities and marginal effects from the model described in (4.8). The distribution- and composition-neutral income elasticity of poverty can be approximated by $\frac{\partial \ln P}{\partial \ln \overline{y}} = \gamma_1$. We expect a positive income elasticity of poverty ($\gamma_1 > 0$), which would imply that a higher mean income corresponds to lower poverty. The income- and composition-neutral inequality elasticity of poverty has a form of a similar type and is approximated by γ_2. We expect a negative inequality elasticity of poverty ($\gamma_2 < 0$), which means that villages with higher inequality are associated with higher poverty rates.

The main focus of this paper is the distribution- and income-neutral elasticity of poverty with respect to changes in the ratios of the underlying cluster proportions, which can be approximated by $\frac{\partial \ln P}{\partial \ln \mathbf{Z_r}} = \beta_r$. The β's can be interpreted as the elasticity of poverty with respect to a change in the number of smallholders in cluster $k \neq B$ relative to those in B.

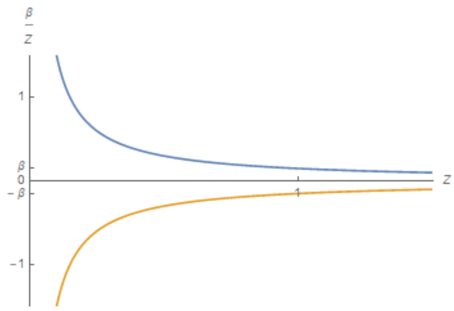
In addition to the elasticities, we also assess the marginal effect of a unit change in $\mathbf{Z}_r$ on the percentage change in poverty. From Equation (4.8), the marginal effect is given by $\frac{\partial \ln P}{\partial \mathbf{Z}_r}$ or

$$\text{Marginal effect} = \frac{\beta_r}{\mathbf{Z}_r} = \beta_{-B} \times \frac{b\mathbf{\Pi}_B}{b\mathbf{\Pi}_{-B}} \tag{4.9}$$

Thus, when the logratio $\mathbf{Z}_r$ increases by 1 unit, poverty changes by approximately $\beta_r/\mathbf{Z}_r \times 100\%$. The marginal effects will always decrease with $\mathbf{Z}_r$: the higher the initial proportion in a cluster relative to B, the weaker the effect of a marginal increase in that proportion on poverty alleviation (for $\beta < 0$) or poverty exacerbation (for $\beta > 0$). These dynamics are illustrated in Figure 4.3 for $|\beta|$. For example, we can interpret an increase in $\mathbf{Z}_{\text{Forest}}$, depicted on the x-axis, as either i) a more smallholders in the forest cluster relative to cropping, ii) fewer smallholders in the cropping cluster relative to forest, or iii) a combination of the two. The effect of this change in the logratio on poverty is non-linear and depends on the initial ratio in the village of smallholders in the forest versus cropping cluster.

Note that if we use the classic approach (i.e. removing one group as the base), we simply need to replace the logratios $\mathbf{Z}_{ir}$ with the cluster proportions $\mathbf{\Pi}_{ik}$ in specification (4.8), leaving one group out as the base. Composition elasticity of poverty is then defined as $\varepsilon_{\mathbf{\Omega}_{-B}} = \frac{\partial \ln(P)}{\partial \ln(\mathbf{\Omega}_{-B})} = \beta_{-B}$ and takes a similar form for the cluster frequencies.

Fig. 4.3 Marginal effect on poverty



Note: Illustration of the marginal effect of the underlying composition Z on poverty, which depends on the initial ratio of Z and the coefficient β. The marginal effect is β when the cluster proportion $-B$ is equal to the proportion of base B, i.e., $Z = 1$. In the illustration, the blue line shows $\beta = 0.15$ and the orange line $\beta = -0.15$ with $Z \in (0, 1.5)$.

However, as mentioned before, these elasticities do not take the compositional nature of the data into account, and can lead to biased results.

Given that our data spans countries in Africa and Asia, it is possible that the elasticities in Equation (4.8) differ between the continents. We examine the robustness of our findings by extending the t-statistic based inference approach of Ibragimov and Müller (2010) to regressions. Specifically, by partitioning the data between Africa and Asia and estimating Equation (4.8) separately for those groups, we allow asymptotically independent normal inference about the parameters that describe the effects of livelihood portfolios. The key result of this partitioning is that our six estimators $\hat{\beta}_r^s$ (each of the cluster frequencies relative to their base) in sample $s \in \{\text{Africa}, \text{Asia}\}$ will be independent so that they are distributed approximately as $\hat{\beta}_r^s \sim \mathcal{N}(\beta_r, v^s)$, with variance v^s, and common mean β_r. The estimated $\hat{\beta}_r$'s can then be treated as independent normal observations (with a common mean but possible unequal variance) and it is safe to carry out a t-test for a level of significance that is less than 8.3% under the null that the common mean β_r is equal to zero (Ibragimov and Müller, 2010).

We use OLS estimation to identify which compositional patterns in terms of livelihood portfolios are associated with lower smallholder poverty. Though poverty measures are theoretically bound between 0 and 1, which would require a different estimation method, in our data the indices never reach these bounds.

4.5 Results

4.5.1 Poverty Regressions

Table 4.6 presents the results of our regression analysis with the poverty headcount (columns (1)-(4)) and poverty gap (columns (5)-(8)) indices as the dependent variables. Recall that the poverty headcount is (only) sensitive to changes in income that lift people out of poverty, i.e., changes that reduce poverty by moving people above the poverty line. The poverty gap ratio is sensitive to changes in income of the poorest which may alleviate poverty, i.e., changes in income that improve the well-being of the poor, even if such changes do not lift people above the poverty line. We therefore interpret the effectiveness of our explanatory variables in terms of poverty reduction (headcount) and poverty alleviation for the poorest (gap).

For the reason of comparison, we include a base regression to analyze the mean income and inequality elasticities of poverty without including the portfolio variables. The results are presented in columns (1) and (5) in Table 4.6 with the poverty headcount and gap as dependent variables respectively. We see, as expected, that the income elasticity of poverty is negative and the inequality elasticity of poverty is positive. In other words, a lower mean income and a more unequal income distribution in villages significantly increase poverty. These elasticities remain significant across the different specifications in the tables. If income portfolios matter, these elasticities suffer from omitted variable bias.

In this paper our focus is on the poverty elasticities of portfolios. These are represented by the coefficients on $Z_{.}$ with the subscript denoting the respective cluster characterisation. The portfolio elasticities are to be interpreted relative to the base group (cropping cluster) and as netted out after controlling for mean income and inequality, i.e., they are level- and distribution-neutral with respect to income. For the poverty headcount, columns (2) and (3) report the estimates for Africa and Asia respectively, and column (4) the common mean and variance per Ibragimov and Müller (2010). For the poverty gap, columns (6) and (7) report the estimates for Africa and Asia respectively, and column (8) the common mean and variance.

For the interpretation of the population effects of differences in portfolios, we draw attention to columns (4) and (8). We have summarised these effects in terms of their sign and significance in Table 4.5. In the next section on marginal effects, we further explore the magnitude of changes in the underlying portfolio on village poverty.

Before proceeding, we want to highlight the substantive significance of coefficient estimators as well as their stability. Clearly, portfolio composition matters to a significant extent for poverty and analyzing poverty without them will result into conclusions based on biased estimators. Significances in some cases appear or disappear depending on whether the focus is on poverty headcount or gap, but signs are preserved across significant results.

Table 4.5 Summary of results - Poverty elasticity of portfolios

VARIABLES	Poverty Headcount	Poverty Gap
Environment		
Z_{Forest} (log)	$-^{**}$	$-^{***}$
$Z_{\text{Non-forest}}$ (log)	$+^{**}$	○
Farm		
$Z_{\text{Livestock}}$ (log)	$+^{***}$	○
Off-farm		
Z_{Wage} (log)	$+^{***}$	$+^{*}$
Z_{Business} (log)	$-^{*}$	$-^{**}$
Z_{Other} (log)	$-^{***}$	$-^{***}$

Note: A summary of the direction and significance of the portfolio elasticities as reported in column (4) and (8) of Table 4.6 in terms of the cluster proportions ($\mathbf{\Pi}$) relative to their base.

Environment

We begin with the poverty effects of the environmental income categories, which consist of forest and non-forest income. We see from Table 4.5 that villages with a higher proportion of smallholders in the forest cluster, relative to those in the cropping cluster, have a significantly lower poverty headcount and poverty gap. Thus, more smallholders in the forest cluster corresponds to both a significant poverty reduction and alleviation in villages. Taking a closer look at these clusters, we note that smallholders in the forest cluster also derive income from cropping, which is their secondary source (on average 17%, see Table 4.4). Similarly, smallholders in the cropping cluster also derive income from forest resources as their secondary source (on average almost 12%). This further highlights the importance of composition, i.e., to which extent these sources are used to generate income.

Interestingly, the regression produces the opposite results in terms of the effect of non-forest environmental income on village poverty. When more smallholders in a village are member of the non-forest cluster relative to the cropping cluster, villages tend to be poorer in terms of poverty headcount. Non-forest income also exacerbates poverty in terms of the poverty gap in Asia, but the population effect is not significant due to the small effect size in Africa.

This opposite result is striking as it suggests that not all types of environmental income are helpful additions to the portfolio. The role of environmental income in poverty has been debated in the literature, with one view that it is a poverty trap and cause of asset poverty, and a counterview that it serves as a safety net and a means to accumulate wealth to exit poverty (Angelsen et al., 2014). We find evidence consistent with the first view when it comes to non-forest resources and evidence suggesting the latter when it comes to forest resources.

We conjecture two possible explanations. The first is to do with the productivity of non-forest extracting activities. In the PEN data set it was found that non-forest environmental income was primarily of the form of subsistence income (i.e., for the household's own consumption), whereas smallholders with income from forests were transforming a larger part to cash income, which can be saved or used to improve (other) livelihood opportunities. We will see this difference between the two portfolios in section 5.3. Another potential explanation is the nature of the goods that are being harvested. As discussed in section 3, non-forest income comprises mainly food products, whereas the uses of forest products are much more diverse in use (building materials, fuel, etc). These two rationales suggest that forests resources may have better income building capabilities than non-forest environmental goods.

Farm
From Table 4.5, we find that livestock, as a cluster membership relative to cropping, only matters for the poverty headcount. Thus, the type of farming income that is used as the primary source (livestock versus cropping) is important for poverty reduction, but not for the alleviation of poverty of smallholders below the poverty line. Once again we note that composition within these clusters is not entirely livestock or cropping: income from cropping in the livestock cluster comprises, on average, 21% of total income (see Table 4.4).

Off-farm
There is a similarly striking result in terms of the effect of the off-farm income category on village poverty as the one we found in the environmental category. The two main components within the category (wage and business) tend to provide the opposite results in terms of their effect on village poverty. Therefore, not all off-farm income

Table 4.6 Poverty Elasticity

	Base	Headcount Ratio			Base	Poverty Gap		
VARIABLES	(1) Mean	(2) Africa	(3) Asia	(4) Mean	(5) Mean	(6) Africa	(7) Asia	(8) Mean
Average income (log)	-2.067***	-2.416***	-1.925***	-2.171***	-3.568***	-4.712***	-3.303***	-4.008***
	(0.263)	(0.426)	(0.382)	(0.347)	(0.631)	(0.792)	(0.653)	(0.996)
Poverty line (log)	2.101***	2.375***	2.151***	2.263***	3.552***	4.689***	3.760***	4.225***
	(0.311)	(0.403)	(0.415)	(0.158)	(0.653)	(0.726)	(0.693)	(0.657)
Gini (log)	1.944***	2.229***	1.875***	2.052***	3.676***	4.174***	3.713***	3.944***
	(0.146)	(0.307)	(0.411)	(0.250)	(0.613)	(0.583)	(0.580)	(0.326)
z_{Forest} (log)		-0.031	-0.069***	-0.050***		-0.056	-0.070	-0.063***
		(0.034)	(0.025)	(0.027)		(0.051)	(0.054)	(0.010)
$z_{\text{Non-forest}}$ (log)		0.093**	0.087**	0.090***		0.002	0.168**	0.085
		(0.039)	(0.039)	(0.004)		(0.094)	(0.063)	(0.117)
$z_{\text{Livestock}}$ (log)		0.093**	0.037	0.065***		0.171**	-0.036	0.067
		(0.038)	(0.034)	(0.040)		(0.077)	(0.046)	(0.147)
z_{Wage} (log)		0.017	0.004	0.010**		0.013	0.085	0.049*
		(0.020)	(0.032)	(0.009)		(0.040)	(0.059)	(0.051)
z_{Business} (log)		-0.051	-0.021	-0.036***		-0.102*	-0.030	-0.066**
		(0.030)	(0.044)	(0.021)		(0.055)	(0.054)	(0.051)
z_{Other} (log)		0.002	-0.029	-0.013		-0.080	-0.073	-0.077***
		(0.059)	(0.031)	(0.022)		(0.109)	(0.053)	(0.005)
Dummy $z_{\text{Forest}} = 0$		-0.054	-0.111	-0.083***		0.209	-0.190	0.010
		(0.092)	(0.129)	(0.040)		(0.176)	(0.171)	(0.282)
Dummy $z_{\text{Non-forest}} = 0$		-0.379***	-0.158*	-0.269***		-0.077	-0.092	-0.085***
		(0.112)	(0.078)	(0.117)		(0.193)	(0.156)	(0.011)
Dummy $z_{\text{Livestock}} = 0$		-0.175**	-0.010	-0.092		0.116	0.080	0.098***
		(0.068)	(0.062)	(0.117)		(0.104)	(0.120)	(0.026)
Dummy $z_{\text{Wage}} = 0$		-0.050	0.017	-0.017		0.085	0.243	0.164**
		(0.077)	(0.079)	(0.047)		(0.124)	(0.232)	(0.112)
Dummy $z_{\text{Business}} = 0$		0.151*	0.310***	0.231***		-0.128	0.293**	0.083
		(0.084)	(0.083)	(0.112)		(0.190)	(0.136)	(0.298)
Dummy $z_{\text{Other}} = 0$		-0.031	0.020	-0.006		0.048	-0.394**	-0.173
		(0.115)	(0.084)	(0.036)		(0.223)	(0.137)	(0.312)
Village controls								
% Community Land [CL]		-0.717***	0.317	-0.200		-0.536	-0.210	-0.373**
		(0.193)	(0.250)	(0.731)		(0.332)	(0.419)	(0.231)
Forest Land (log) [FL]		0.111**	-0.136***	-0.013		0.139	-0.085	0.027
		(0.041)	(0.043)	(0.175)		(0.089)	(0.088)	(0.158)
CL × FL		-0.133**	0.053	-0.040		-0.173	-0.007	-0.090
		(0.051)	(0.072)	(0.132)		(0.102)	(0.122)	(0.117)
Constant		3.375***	-0.264			5.209***	0.181	
		(0.826)	(0.856)			(1.640)	(1.364)	
Country dummies	No	Yes	Yes	-	No	Yes	Yes	-
Observations	2	37	43	2	2	37	43	2
R-squared		0.885	0.845			0.895	0.837	
Adjusted R-squared		0.770	0.728			0.790	0.715	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

seems to be equally desirable in a village portfolio. Specifically, in terms of wage as a livelihood strategy, we find that villages with a higher average proportion of smallholders in the wage cluster, relative to those in the cropping cluster, have significantly higher poverty headcount and poverty gap ratios. On the other hand, villages with a higher proportion of smallholders in the business cluster relative to the cropping cluster have a significantly lower poverty headcount and poverty gap. As such, business income as a primary strategy tends to align with village poverty reduction and alleviation.

4.5.2 Marginal Effects

The regression analysis presented above adds significantly to our understanding of the effects of smallholders' livelihood selection on poverty, but per Equation (4.9), we know that the marginal effect, or the magnitude, of changes in portfolios on poverty depends on the relevant elasticity as well as on the initial portfolio composition. Thus, the marginal effects show us how to tailor the livelihood strategy approach to villages that differ in terms of their initial compositional pattern. When the coefficient is smaller than zero, a higher cluster proportion across villages relative to cropping has a poverty alleviating affect. However, this effect is lower, the greater is the initial proportions of that cluster relative to cropping (Z). Thus, when $\beta < 0$ and the cluster is 'underdeveloped', it should be grown. If $\beta < 0$ while that income component or cluster already constitutes a sizable part of the village portfolio, it is much less a priority. Conversely, when $\beta > 0$, we must avoid growth in that source or cluster, since it can exacerbate poverty, and grow the base group instead. The poverty effect of growth, however, is much weaker if that component or cluster already has a large initial proportion compared to the base.

As a counterfactual analysis, we evaluate the marginal effects of the cluster memberships at three magnitudes: the median ratios (Z_r) of the 80 villages, and the ratios of the 10^{th} and 90^{th} percentiles. The results are presented in Table 4.7. We focus on the significant population effects which are reported in bold.

Table 4.7 Marginal effects of compositional changes

	Headcount Ratio			Poverty Gap		
	Median	10^{th} Pctl	90^{th} Pctl	Median	10^{th} Pctl	90^{th} Pctl
Environment						
$\beta_{\text{Forest}}/Z_{\text{Forest}}$	**-0.05**	**-0.45**	**-0.003**	**-0.063**	**-0.567**	**-0.004**
$\beta_{\text{Non-forest}}/Z_{\text{Non-forest}}$	**0.114**	**0.564**	**0.04**	0.107	0.533	0.038
Farm						
$\beta_{\text{Livestock}}/Z_{\text{Livestock}}$	**0.067**	**1.002**	**0.008**	0.069	1.033	0.008
Off-farm						
$\beta_{\text{Wage}}/Z_{\text{Wage}}$	**0.013**	**0.097**	**0.001**	**0.064**	**0.476**	**0.006**
$\beta_{\text{Business}}/Z_{\text{Business}}$	**-0.076**	**-0.288**	**-0.008**	**-0.140**	**-0.528**	**-0.016**
$\beta_{\text{Other}}/Z_{\text{Other}}$	-0.052	-0.192	-0.002	-0.308	-1.138	-0.011

Note: Marginal effects are evaluated at the median, 10^{th} and 90^{th} percentile of the logratios of the cluster proportions ($\mathbf{\Pi}$). The marginal effects with a significant β_r (Table 4.6) are reported in bold.

Environment

As we know from the previous section, a higher proportion of smallholders in the forest cluster reduces and alleviates poverty, but the responsiveness of poverty also depends on the initial ratio of forest cluster members over cropping cluster members. Specifically, at its median value, an 0.01 unit increase across villages in the ratio of smallholders in the forest cluster over the those in the cropping cluster reduces the poverty headcount ratio by 0.05% and poverty gap by 0.063%. Evidently, the effect sizes are much larger when a village's initial cluster proportions score in the 10^{th} percentile than at the median (or at the 90^{th} percentile). For example, a 0.01 unit increase in the proportion of smallholders in the forest cluster, relative to those in the cropping cluster, corresponds to 0.45% fewer people below the poverty line when the initial ratio is in the bottom 10^{th} percentile and only 0.003% fewer people below the poverty line when the initial ratio falls in the 90^{th} percentile. Especially for those villages where the initial proportion is relatively low, the importance of natural resources should not be overlooked just because other income clusters may have higher elasticities.

Note that at its median value, the marginal effect of the forest cluster on poverty is the same as the coefficient for the elasticity (Table 4.6). Recall from Figure 4.3 that this implies that at its median, the proportion of smallholders in the forest cluster is similar to the proportion of smallholders in the cropping cluster ($Z_{\text{Forest}} \approx 1$). The marginal effect of changing this ratio across villages that fall around this median value is approximately the elasticity. If the initial composition is such that the proportion in the forest cluster is lower (e.g. 10^{th} percentile), the marginal benefit of increasing this ratio is substantially higher than the elasticity.

Moving to the effects of having non-forest income in a village portfolio, recall that a higher proportion in non-forest income or in the non-forest cluster exacerbates poverty. Interestingly, the marginal effect on the poverty headcount of the non-forest cluster at its median value is much higher than its corresponding elasticity. This implies that the proportion of smallholders in the non-forest cluster must be lower than the proportion smallholders in the cropping cluster, i.e., ($Z_{\text{Non-forest}} < 1$) at the median value of $Z_{\text{Non-forest}}$. Thus, the marginal effect on poverty reduction of reducing smallholders in the non-forest cluster relative to those in the cropping cluster is higher than the elasticity for the majority of villages.

Farm

The farm income source is relevant for poverty reduction, but does not correspond to a significant change in poverty alleviation. We can see that at its median, a increase of 0.01 in the number of smallholders in the livestock cluster relative to those in the cropping cluster corresponds to 0.067% higher poverty headcount rate. Since this is only slightly higher than the corresponding elasticity, we know that at the median, the proportion of livestock income is approximately that of cropping income ($Z_{\text{Livestock}} \approx 1$) and the marginal effect across villages around the median of changing this ratio is approximately the elasticity.

Off-Farm

Off-farm income, depending on the exact source, corresponds to either poverty reduction and allevation, or poverty exacerbation. Let us start with the marginal effect of the proportion of smallholders in the wage cluster. A 0.01 unit increase in the ratio of smallholders in the wage cluster over those in the cropping cluster increases the poverty headcount by 0.013% and the poverty gap by 0.064%. Again, we can see that at its median, $Z_{\text{Wage}} < 1$ and as such a reduction in this ratio reduces and alleviates poverty to a greater extent than the elasticity would suggest across the majority of villages.

Moving to business income, recall that we found evidence of strong poverty reducing and alleviating effects. Now we see that this is not only because poverty is particularly elastic with respect to business income and cluster proportions, but also because they are relatively underdeveloped. Specifically, at its median, we find that $Z_{\text{Business}} < 0.5$; thus twice as many people are in the cropping cluster in the average village. This would suggest that a higher number of smallholders in the business portfolio across villages, at or below the median, is a exceptionally effective measure for reducing and alleviating poverty.

To summarise, the effect of changes in cluster membership on poverty depends not only on poverty elasticity of portfolios, but also on the initial portfolio composition in the village. Specifically, the marginal effects of changes in cluster proportions across villages is highest when there are fewer members in these clusters compared to cropping. Evaluated at their median values, the non-forest cluster constitutes a similar size as the cropping cluster, whereas the wage cluster has a smaller membership than cropping. This can make changes across villages in the wage cluster, relative to cropping, more pronounced in their effect on poverty than changes in the non-forest cluster despite the fact that the elasticity of the wage cluster is lower than the non-forest cluster elasticity. Similarly, the business and forest clusters are a key pathway out of poverty (relative to cropping), with both poverty reduction and alleviation for the poorest highly responsive to these regressors. The poverty elasticity with respect to forest income is higher, which would imply that this cluster would be an effective tool to poverty alleviation. However, in the majority of villages in our data set the business cluster has very few members relative to the cropping cluster, making the marginal effect of changes greater despite its lower elasticity. The target of intervention should therefore depend on the initial composition in the village.

4.5.3 Cluster membership characteristics

Village poverty is most responsive to changes in the clusters, and cluster proportions provide more precise estimates of the relationship between portfolios and poverty. If we wish to leverage the insights gained from clusters, it would be useful to know the extent to which smallholders grouped in different clusters have different characteristics. Thus, as a last step, we profile our clusters on external variables that were not included in the clustering process. Specifically, we attempt to identify whether there are demographic and other differences between smallholders that pursue the 'winning' and 'losing' portfolios.

We perform pairwise comparisons (one-tailed two-sample t-tests) for the differences between clusters in terms of the mean characteristics of their members. First, we compare mean total household income and mean headcount ratio per cluster, i.e. the proportion of households in that cluster that fall below their respective village-level poverty line, both of which entered our regression specification on the village level. Second, we compare demographics, including the gender, age, and education of the household head, household size, and whether the household is a member of a "Forest User Group" (an organised group of people who use and maintain the community forest). Further, we look at the location of the households, including the number of hours members of the household need to walk on average to the forest and the village centre. In addition, we assess the average endowment of households, such as the plot size of the agricultural and forest land owned by the household, the value of assets (e.g. furniture, material of the house), and the average percentage of cash income over total income as a proxy for market integration.

To further explore a cluster's diversity of operations in terms of livelihood activities, we calculate the Jacquemin-Berry entropy measures for each cluster, per Palepu (1985). The index considers the degree of relatedness among the various income segments and allows the decomposition of total diversity into two additive components: (1) an 'unrelated' component that measures the extent to which a smallholder's income is derived from unrelated sources (e.g. Environment and Off-farm) and (2) a related component that measures the distribution of the output among related sources within the income categories (e.g. cropping and livestock). We report the total diversification and the unrelated component.

We highlight a few variables that significantly characterise certain clusters. The results are reported in Table 4.8. The superscripts indicate the means of clusters that are not significantly different from each other. Recall that the 'winning' portfolios are the business and forest cluster. The 'losing' portfolios are the non-forest, wage, and, in the case of the headcount ratio, the livestock cluster.

From the first two rows we can see that the business cluster has a significantly lower headcount ratio and higher total income than any of the other clusters. We also see that the non-forest cluster has the highest headcount and lowest mean income. These are mean differences, but they are corroborated by the regression results.

Table 4.8 Smallholder characteristics by cluster membership

VARIABLES	Cluster 1 Forest	Cluster 2 Non-forest	Cluster 3 Cropping	Cluster 4 Livestock	Cluster 5 Wage	Cluster 6 Business	Cluster 7 Other
Headcount (%)	$25.14^{3,5}$	35.26	$27.58^{1,5}$	$17.12^{6,7}$	$25.38^{1,3}$	$14.66^{4,7}$	$17.28^{4,6}$
	(1.62)	(2.17)	(1.47)	(1.55)	(1.61)	(2.02)	(1.94)
Total Income	$1267.70^{4,7}$	$868.95^{3,5}$	$919.80^{2,5}$	$1294.06^{1,7}$	$941.57^{2,3}$	2047.47	$1386.80^{1,4}$
	(51.16)	(81.55)	(42.66)	(50.41)	(31.62)	(185.90)	(64.20)
Household size	$3.73^{2,5}$	$3.81^{1,5}$	$4.12^{6,7}$	4.43	$3.77^{1,2}$	$4.08^{3,7}$	$4.03^{3,6}$
	(0.054)	(0.081)	(0.069)	(0.090)	(0.058)	(0.118)	(0.088)
Female head (%)	$12.15^{3,5,6}$	$16.70^{2,6,7}$	$12.24^{1,5,6}$	9.32^{6}	$12.84^{1,3,6,7}$	$13.03^{1:5,7}$	$16.49^{2,5,6}$
	(1.22)	(1.70)	(1.07)	(1.20)	(1.24)	(1.92)	(1.90)
Age head	$42.81^{5,6}$	45.88^{3}	$46.56^{2,4}$	47.49^{3}	$43.41^{1,6}$	$42.70^{1,5}$	51.92
	(0.492)	(0.688)	(0.491)	(0.601)	(0.487)	(0.702)	(0.863)
Education head (years)	4.37^{5}	3.57	3.98	3.10^{7}	4.45^{1}	5.04	2.93^{4}
	(0.134)	(0.175)	(0.128)	(0.151)	(0.161)	(0.218)	(0.187)
FUG member (%)	$23.18^{5,6}$	11.78	18.90	33.39	$26.78^{1,6}$	$23.45^{1,5}$	44.24
	(1.58)	(1.47)	(1.28)	(1.94)	(1.64)	(2.42)	(2.54)
Distance forest (hours)	0.408^{5}	$0.681^{4,6,7}$	0.537	$0.629^{2,6,7}$	0.442^{1}	$0.669^{2,4,7}$	$0.677^{2,4,6}$
	(0.019)	(0.038)	(0.022)	(0.032)	(0.017)	(0.044)	(0.026)
Distance village center (hours)	$0.344^{2,3,4,5}$	$0.355^{1,3,4,5}$	$0.370^{1,2,4,5}$	$0.349^{1,2,3,5}$	$0.360^{1,2,3,4}$	0.299	0.566
	(0.017)	(0.022)	(0.015)	(0.020)	(0.017)	(0.025)	(0.033)
Agricultural land (ha)	0.898^{2}	0.950^{1}	1.079	0.790^{5}	0.747^{4}	0.556	1.863
	(0.041)	(0.051)	(0.045)	(0.047)	(0.039)	(0.038)	(0.187)
Forest land (ha)	0.597^{7}	$0.368^{5,6,7}$	$0.193^{4,5,7}$	$0.164^{3,5,7}$	$0.245^{2,3,4,6,7}$	$0.340^{2,5,7}$	$0.836^{1:6}$
	(0.071)	(0.077)	(0.024)	(0.044)	(0.042)	(0.072)	(0.542)
Total land	1.620^{7}	1.373^{3}	1.379^{2}	$1.035^{5,6}$	$1.037^{4,6}$	$0.925^{4,5}$	2.868^{1}
	(0.111)	(0.096)	(0.056)	(0.065)	(0.063)	(0.085)	(0.775)
Total assets	315.71^{3}	166.09^{5}	261.93^{1}	460.98	193.29^{2}	1196.57^{7}	924.38^{6}
	(45.06)	(24.56)	(27.36)	(66.13)	(22.53)	(200.13)	(103.14)
Market integration (%)	56.62^{4}	47.76^{3}	48.66^{2}	56.60^{1}	72.14	78.20	66.31
	(0.90)	(0.96)	(0.86)	(0.90)	(0.66)	(0.87)	(0.85)
Total diversification	1.120^{6}	1.365	1.028	1.210^{7}	1.160	1.082^{1}	1.203^{4}
	(0.011)	(0.013)	(0.012)	(0.012)	(0.012)	(0.022)	(0.017)
Unrelated diversification	0.814^{7}	0.903	$0.721^{4,6}$	$0.723^{3,6}$	0.859	$0.747^{3,4}$	0.833^{1}
	(0.008)	(0.010)	(0.009)	(0.010)	(0.008)	(0.017)	(0.011)

Note: The mean across smallholders within a cluster is reported with the standard error between brackets. Superscripts denote non-significant differences, i.e. the clusters between which the means are not significantly different from each other using a 5% significance level.

Demographics

Many household characteristics differ between clusters, and we will focus on some of the important differences. The first notable feature is that smallholder household heads in the off-farm clusters (business and wage) have had significantly more years of education than the heads in farm and non-forest clusters. Interestingly, household heads in the forest cluster completed an average of 4.37 years of education, which is on par with those in the wage cluster. This is surprising as education is usually regarded as a means to improve off-farm labour opportunities, and can be expected to reduce the returns from engaging in extractive activities that are characterised by higher labour intensity (Angelsen et al., 2014). The fact that wage income is typically a secondary or tertiary income source for smallholders in the forest cluster could explain this dynamic.

Another point of similarity between the business and forest cluster is the relatively high proportions that are members of a Forest User Group (FUG); the non-forest cluster has the lowest FUG membership. Recall that even when business or non-forest are the primary strategies, forest is still an important secondary or tertiary source. Two types of arguments favour the proposition that FUG membership influences the success of a cluster. First, the members may have privileged access to forest resources, especially as active forest users are likely to self-select into membership. As a result, a cluster with high FUG membership is likely to have more successful smallholders. Causality, however, can also work the other way round. Management of the forest resources becomes stricter when there are more participants. As such, FUG members are restrained from overly intensive use, in favour of safeguarding the natural resources and thus providing better income opportunities for the poor.

Location and Endowment
Smallholder distance from key areas, and their assets endowment characteristics, may shed further light on possible determinants of and barriers to cluster membership. Smallholders in the forest and wage cluster tend to live closest to the forest, but smallholders in the forest cluster also have significantly more forest land, as well as significantly more total land area than the other clusters. Previous studies have found that forest resources are more sustainably extracted the greater the land area owned by local communities (PEN, 2020). Thus, land ownership being significantly higher for members in the forest cluster and land ownership being a significant determinant of the sustainable use of forests go hand-in-hand. Though smallholders in the wage cluster have a close proximity to forests, the lack of land as a key productive asset in the wage group may have inhibited smallholders from developing their forest income in a sustainable manner.

Smallholders in the livestock, business, and wage clusters own the least amount of land, but unlike the smallholders in the livestock and wage group, the regression analysis suggested that this does not inhibit the business cluster's ability to reduce poverty. We also see that smallholders in the business cluster live on average closest to the village center and are endowed with the most assets other than land. Since business is non-extractive, these characteristics could be part of the explanation why the business cluster fares relatively well with little land while the livestock and wage clusters do not.

Smallholders in the "other income" cluster have the most land, but we note that this cluster typically has a very high standard error of the mean. Since household heads are significantly older in this group, it could suggest that these households have accumulated more assets over time (Angelsen et al., 2014). It also suggests that these households are not using those assets as productively as they could, since we would expect them to derive more income from those sources.

Integration and Diversification
The market integration, i.e., the proportion of cash income in total income, is clearly higher for the clusters that are focused on off-farm income. This is to be expected as wage and business incomes typically come in cash, whereas the products from environmental and farming activities can be marketed goods, which are converted into cash, or non-marketed goods, which are not converted and e.g. used for own consumption. Typically, the ability to generate cash from an income source (i.e., higher market integration) is associated with greater prosperity, whereas the converse is associated with lower income (Angelsen et al., 2014). We note that households in the forest and livestock cluster have a higher proportion of cash income than those in the non-forest and cropping cluster.

Lastly, the entropy measures present an interesting picture in terms of specialisation versus diversification. The smallholders pursuing the winning clusters, i.e, forest, cropping, and business, are the most specialised, whereas those in the losing clusters, i.e., non-forest and livestock, are most diversified. Moreover, the non-forest and wage portfolios involve significantly more diversification into unrelated sources. This could suggest that smallholders should attempt to specialise their activities, and their diversification should be into related income sources.

4.6 Discussion and practical implications

Our analysis shows that there is substantial diversity of income strategies pursued by smallholders, and that the constituent income components of livelihood strategies are significant determinants of poverty. Governments and non-profits working to reduce and alleviate poverty should inform their strategies with detailed considerations of livelihood portfolios. Similarly, multinationals who source commodity goods from these smallholders should not neglect the importance of the other income sources that make up the complete livelihood portfolio of these smallholders when working to meet their sustainability and poverty commitments. Solely focusing on farming income or income at the aggregate is insufficient.

This is all the more important, as we find that income components affect poverty in different ways and even those within the same broad category (environment, farm, off-farm) often act in opposite directions. This finding highlights the danger of drawing conclusions based on aggregate income. For instance, we find that while forest income is a welcome addition to a livelihood portfolio relative to cropping, non-forest income tends not to be. This suggests that non-forest environmental resources may function as a poverty trap, whereas forest resources may provide a safety net. Deep understanding at the disaggregated-level is a sounder basis for operational interventions that help smallholders to select and construct poverty alleviating income combinations.

Our results suggest that village portfolios containing smallholders in the business and forest clusters form a key pathway out of poverty. Specifically, a higher proportion of smallholders being members of the business or forest cluster relative to the cropping cluster corresponds to poverty alleviation for the poor, as well to more smallholders escaping poverty. The poverty measures are most elastic with respect to the forest component, however, the business cluster is underdeveloped for the majority of villages in our data set. Since the marginal effect is enhanced if a cluster proportion is underdeveloped in a village relative to cropping, the developing the business cluster may have greater effects on poverty despite its lower elasticity.

It is beyond the scope of this study to understand the precise mechanism through which increased business and forest clusters relative to cropping counter poverty, but we provide some conjectures for future work. One potential explanation is that increased agricultural production typically reduces agricultural prices (Sunderlin et al., 2005). As such, when more smallholders pursue cropping as their primary livelihood, it could generate a downward pressure on prices. When it comes to business income, there generally are many more opportunities for diversification. When more villagers seek and earn business income with cropping a non-primary income source, this move can reduce within village competition and reduce pressure on commodity prices. Moreover, there are fewer land trade-offs to make between environmental and off-farm income than between environmental and farm income. Given that we indeed find that smallholders in the business cluster fare well with the lowest level of land ownership, livelihood portfolios could become more sustainable as the dependence on agricultural land diminishes.

We find that villages with more smallholders earning forest-based livelihoods relative to cropping, are associated with a significantly lower poverty headcount and poverty gap. Again, we do not attempt to explore the exact underlying mechanism, but we conjecture the following. First, similar to the business cluster, a movement to forest income with cropping as a non-primary income source can reduce pressure on commodity prices. Forest resources have a wide range of uses and markets (much more than e.g. non-forest environmental resources), including wood fuels (firewood, charcoal, etc), food (fish, bushmeat, fruits, mushrooms), and structural and fibre products (poles, sawn wood, leaves, grass) which are either sold or used for own consumption. A good level of diversification is therefore possible.

Moreover, it is a well-known fact that farming and environmental income compete for land resources. As cropping is replaced by forest resources as the primary livelihood, forests become less pressured by agricultural expansion. Preservation of these forest resources helps the most vulnerable households in the village who rely on forests for their safety nets, reducing and alleviating village level poverty. Evidently, the resources should be harvested sustainably as our results suggest that the degradation of forest resources can have grave welfare implications. Specifically, if forest resources disappear due to unsustainable extraction, smallholders will have fewer livelihood portfolios to choose from and likely become worse off.

Whether the extraction is in fact sustainable is a different matter. A recent report by the Food and Agriculture Organization of the United Nations suggests that the development of forest-based livelihoods through a diversified portfolio of forest products and services can help preserve these resources by increasing their value for local communities and encouraging sustainable production (FAO and UNEP, 2020). Further research is necessary on the environmental front, but this would imply that facilitating (sustainable use of) forest resources can help both social goals, as we show it increases benefits and functions for people in poverty, as well as environmental goals.

Governments and trans-national agencies alike who have a mission of eradicating poverty should also focus on removing potential barriers to income portfolios that have more beneficial effects. When we investigate characteristics of smallholders in the business and forest cluster, we find that they have relatively higher education and their land and location supports their primary livelihood strategy, i.e., smallholders in the business cluster live closest to the village center and need very little land, reducing pressure on forests. Smallholders in the forest cluster are closest to the forest and command the largest forested area.

For the operationalisation of these results, we recommend a systemic approach that manages income components and portfolios simultaneously, rather than focusing on a single sub-component or on a subset of smallholders. The aggregation of supply and demand of agricultural goods is currently developed, where smallholders in a region are combined in a 'Producer Organisation' to limit inefficiency in sourcing when firms have to deal with smallholders one-on-one (IFC, 2013). We suggest that the efficacy of livelihood interventions or procurement strategies aiming to achieve prosperity can be meaningfully enhanced by extending smallholder aggregation beyond just agricultural products. Specifically, if all demands for environmental, farm, and off-farm products and services by firms, social enterprises, and SMFEs are aggregated, village portfolios can be managed, rather than individual components. This need to coordinate becomes especially relevant as more firms and agencies source directly, simultaneously, but independently from each other. Practically speaking, a system like this can be coordinated by NGOs, but also by village leaders or councils which all villages in our data set have.

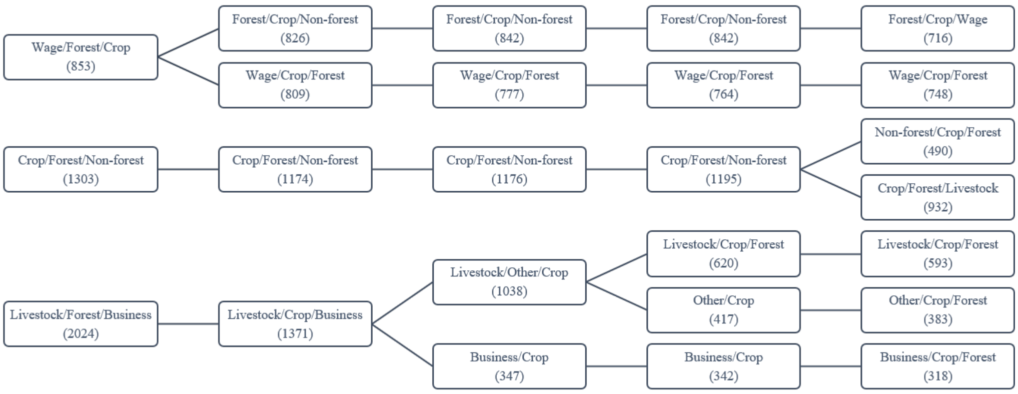
Though household level survey data has several advantages as explained in the paper, there are two drawbacks. The first is that obtaining panel data at this micro-scale is costly. The cross-sectional PEN data collection by the Center for International Forestry research (CIFOR) in collaboration with universities and regional and international institutions from various countries took 12 years to complete. Needless to say, conducting several replications of a study of this scale is not feasible. However, the insights derived from cross-sectional analysis of this large data set can point the way to new lines of inquiry and guide smaller, more focused studies, to understand the most important mechanisms that work with specific livelihood portfolios and subsequently move from a static observation to a dynamic approach.

The second drawback is one of data integrity. All surveys suffer from the fact that households may under-report incomes. Studies have shown that income derived from business is generally under reported due to tax concerns (Hurst et al., 2014). Since business income is associated with lower poverty rates, under reporting of business income would likely strengthen our main results. Forest income has also been found to be under reported by rural households extracting at least 25% of their income from this source; this may lead to upwardly biased national poverty estimates (Parvathi and Nguyen, 2018). In our analysis, we focus exclusively on rural poverty and find that a higher share of forest income is typically associated with less poverty among rural smallholders. Thus, upward income corrections in forest income are also likely to strengthen these results. However, there is a possibility that the *extent* of under reporting is greater for the rural poor than the rural non-poor, given a certain income share that is extracted from forestry. If the poor systematically under report their forest income to a greater extent than the non-poor, inferences could become weaker. Further research into reporting differences between socio-economic groups within the rural community should be useful in accounting for possible biases in studies using rural survey data.

4.7 Appendix

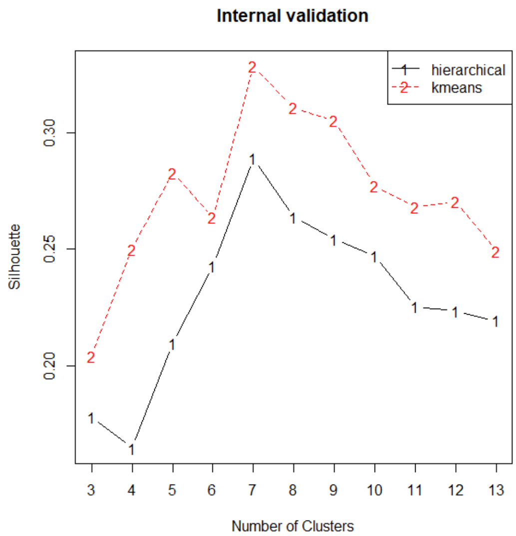
4.7.1 Cluster Analysis

Fig. 4.4 Cluster Hierarchy



Note: Cluster formation by primary mean livelihood sources for $K = 3$ to 7 using K-means clustering, performing 5,000 runs of randomly drawn initial starting seeds. Number of observations are reported in brackets.

Fig. 4.5 Silhouette Width of K-means and Ward



Note: The Silhouette Width is the average of each observation's Silhouette value. The Silhouette value measures the degree of confidence in a particular clustering assignment and lies in the interval [-1,1], with well-clustered observations having values near 1 and poorly clustered observations having values near -1. K-means lies strictly above Ward's hierarchical algorithm, with $K = 7$ leading to the best clustering outcome, attesting to the internal validity of our centroid selection as well as the relative validity of using K-means.

Table 4.9 Centroid Selection Choices

Cluster $K = 5$	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Observations	842	1176	1038	777	347
Primary source	Forest	Crop	Livestock	Wage	Business
Primary mean	51.26%	56.41%	32.18%	49.51%	54.30%
Primary min	14.75%	20.89%	0.00%	17.60%	18.89%
Within SS	70.1	89.0	169.6	62.5	33.8
Total Between SS/Total SS	54.5%				

Cluster $K = 6$	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Observations	842	1195	620	764	342	417
Primary source	Forest	Crop	Livestock	Wage	Business	Other
Primary mean	50.71%	55.76%	47.10%	49.72%	54.59%	48.53%
Primary min	0.00%	8.50%	8.27%	18.07%	18.89%	13.91%
Within SS	76.4	95.3	48.2	59.3	32.8	33.0
Total Between SS/Total SS	63.1%					

Cluster $K = 7$	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Observations	716	490	932	593	748	318	383
Primary source	Forest	Non-forest	Crop	Livestock	Wage	Business	Other
Primary mean	54.77%	30.74%	60.98%	48.17%	50.26%	56.48%	50.58%
Primary min	25.17%	0.51%	34.70%	21.21%	21.46%	25.89%	24.44%
Within SS	48.2	45.0	58.6	41.9	56.7	27.1	27.3
Total Between SS/Total SS	67.3%						

Note: Cluster formation by primary mean livelihood sources for $K = 5$ to 7 using K-means clustering, performing 5,000 runs of randomly drawn initial starting seeds. Mean and minimum contribution of the primary source to total income is reported, as well as the within Sum of Squares within each cluster, which shows how similar households within one cluster are. Total Between Sum of Squares over the Total Sum of Squares shows how distinct households between clusters are. When $K = 7$, the minimum contribution of the primary source within the cluster is non-zero.

4.7.2 Income Proportions

We construct the correlations between average income proportions (ω_i) and cluster proportions (π_i) which are reported in Table 4.10. We also look at the correlation between the logratios, which are the regressors. We confine ourselves to the values different from zero, as per the Battese technique, the effect in case of zero values will be captured by the dummies rather than by the coefficients of the regressors themselves.

The two types of portfolio measures are highly correlated, which means that villages with a higher average proportion in source q also tend to have more smallholders in the cluster where source q is the primary source (and vice versa). We therefore expect the coefficients of the regressors to be highly consistent with each other.

Table 4.10 Correlation matrix of portfolio proportions

	Forest	Non-Forest	Cropping	Livestock	Wage	Business	Other
Proportions	0.956***	0.923***	0.938***	0.953***	0.960***	0.945***	0.925**
Logratios $\neq 0$ (log)	0.928***	0.753***	-	0.918***	0.922***	0.837***	0.902***

The variance of the cluster proportion across villages is either equal to or significantly higher than that of the income proportions, for both Africa and Asia. Higher variation in the regressor helps pin down the effect of cluster proportions on poverty with increased precision, making the estimates on the cluster proportions more reliable. Thus, despite the significantly high correlation between the income source and income cluster portfolio regressors, the reliability of the conclusions drawn can differ depending on variation in the data. Applying the portfolio measure that generates the most reliable and precise estimate is especially relevant in developing country contexts where sample sizes are often small.

Table 4.11 Hypothesis test of regressor variances

	Africa			Asia		
	Cluster s	Income source s	p-value	Cluster s	Income source s	p-value
Environment						
Forest	1.988	0.987	0.000	1.669	0.907	0.000
Non-Forest	1.133	0.912	0.105	0.974	1.259	0.102
Farm						
Livestock	1.360	1.043	0.067	1.727	1.234	0.019
Off-farm						
Wage	1.574	1.537	0.442	1.329	0.952	0.019
Business	1.215	1.136	0.348	1.463	1.500	0.448
Other	0.854	0.949	0.325	1.846	1.572	0.175

Note: To test whether the variances s^2 of the cluster logratios are higher than those of the matching income source logratios, we use $F_c = \frac{s^2_{\Pi_r}}{s^2_{\Omega_r}} \sim F_{n_{\Pi_r}, n_{\Omega_r}}$ and test $H_0 : \sigma^2_{\Pi_r} = \sigma^2_{\Omega_r}$ against $H_1 : \sigma^2_{\Pi_r} > \sigma^2_{\Omega_r}$. If the variance of the income source logratio is larger than that of the cluster logratio, we inverse the statistic.

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Chapter 5

Conclusion

The chapters in this dissertation uncover new opportunities for research on the Sustainable Development Goals by fostering the link between scientific communities (economics and operations management) as well as the link between academia and practice (Europol and the United Nations). Supply chain management, as a cross-cutting topic that applies to several issue areas, has an enormous opportunity to make a difference, especially when scholars take a broader view of its role in society. I briefly summarise the main findings in this section.

Chapter 2 built on the work on the triple-A supply chain and revisited the definitions of agility, adaptability, and alignment given the new demands of social and environmental sustainability. The new definitions emphasise the importance of responding to a broader set of stakeholders, of developing innovative processes to control supply chains or innovative business models that create new supply chains, and of expanding the view of supply chain alignment, up- and downstream, through improved visibility. This framework can help firms tackle the growing challenges that sustainability and circularity present to their supply chains.

Chapter 3 explored in depth the problem of social and environmental violations in the waste management chain, given the complex interactions between firms' incentives to comply and policy interventions. Illegal waste export and dumping can undermine social and environmental goals due to heavy pollution and society's inability to recover scarce resources. Incomplete information characterises the market and can negatively or positively impact compliance through firm interactions. Policy setting plays a decisive role in the compliance outcome. Current policy that primarily focuses on discouraging the export of low-quality waste can backfire and create perverse incentives for firms. Driven by moral hazard and adverse selection, prices increase, illegal disposal becomes more attractive, and profits of compliant firms are undermined, thereby attaining the opposite of what was intended. Regulating the export of high-quality waste more closely is a powerful tool to avoid this trap by ensuring that the opportunity cost of serving the full waste market compared to only serving the low-end waste market is not too high.

Export regulations on high-quality waste can be complemented by domestic anti-dumping enforcement efforts to ensure the best possible waste management outcome is attained. An increase in the dumping cost for the manufacturer is an effective measure that reduces the manufacturer's willingness to pay when dumping activities occur and can expand the scope of waste treatment. However, such domestic enforcement efforts should be carefully tailored in conjunction with export regulations so they do not backfire by undermining profits of efficient operators or even worsening waste outcomes.

Chapter 4 analysed how rural livelihood portfolios bear upon poverty, explicitly incorporating the proven importance of natural resources for rural smallholders who live close to forested areas. We know that a growing number of companies and social enterprises are sourcing directly from poor smallholders in developing countries, but the dependencies between income components that make up smallholder livelihood portfolios are not yet well understood. Our empirical analysis shows that portfolio compositions are a significant determinant of poverty outcomes, with some combinations having poverty alleviating capabilities while others tend to exacerbate poverty in villages. Notably, portfolios that feature income sources that fall within the same broad-level category (environment, farm, off-farm) often affect poverty in conflicting directions. It is therefore all the more important that organisations adopt a systemic approach that designs and manages smallholders' income components simultaneously as a holistic portfolio rather than focusing on a single sub-component.

Last year marked the start of the last decade before the Sustainable Development Goals are due in 2030. Both the private and public sector will have a role to play in combating global challenges — ranging from climate crises and extreme poverty to the rapid degradation of the natural environment. These stakeholders are in need of solutions to help attain the SDGs, some of which supply chain sustainability can deliver. Unfortunately, companies rank supply chain practices as the biggest challenge to improving their sustainability performance, especially given the complex interdependencies between the goals. Many of these interdependencies are still unexplored, but an expanded scope can connect the underlying issues to a greater set of solutions. As such, future research that is cross-disciplinary and rooted in multi-stakeholder collaborations will be key in this pivotal moment.