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RESEARCH ARTICLE

Optimizing microplastic pollution in a terrestrial environment: a case for soil-biodegradable mulches

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Abstract

Microplastic pollution from plastic fragments accumulating in agricultural fields threatens the world's most productive soils and environmental sustainability. This is the first paper to address the challenge of developing a dynamic economic model to analyze the adoption of soil-biodegradable plastic mulches (BDMs) as a sustainable alternative to conventional polyethylene mulches. The model considers the trade-off between BDM degradation rates and agricultural production, seeking to balance the cost of BDMs and the cost of waste disposal. We consider both private and social perspectives under deterministic and stochastic environments. Our findings suggest that BDMs can significantly decrease long-term plastic pollution from single-use plastics in agriculture. For example, increasing landfill tipping fees incentivizes Washington State tomato growers to optimally adopt BDMs with a 61% degradation rate and to till used BDMs into the soil, reducing plastic waste accumulation in landfills. The study highlights the role of economic incentives, such as landfill fees, corrective taxes and the role of risk aversion, in promoting BDM adoption and curbing plastic pollution. The framework presented here offers valuable insights for policymakers and stakeholders seeking to foster sustainable agricultural practices and mitigate global plastic pollution.

Keywords: Agro-ecological system; corrective tax; landfill tipping fee; microplastic pollution; soil-biodegradable plastic mulches; soil pollution

JEL Classifications: Q57; Q52; Q53; Q55; Q58; C61

Introduction

The popular use of plastics in agriculture, while boosting productivity (Ingman et al 2015; Steinmetz et al 2016) and ensuring food security in the short run (Brodhagen et al 2017;

Coskun et al 2017), has caused a pressing environmental dilemma (Rochman 2018). Conventional plastic products, like those made from polyethylene, have increased crop yields across the world. For example, cotton, maize, and wheat yields have increased by 30% in China (Bloomberg 2017). Polyethylene mulches (PEMs) are a prime example of beneficial plastics for food production, widely used in commercial agriculture around the world.[1] The scale of their use is substantial: U.S. farmers alone use 1 billion pounds of plastic annually, with 40% being plastic mulches (Kirkham et al 2020). In China, a staggering 1.45 million metric tons of plastic mulches covered nearly 50 million acres of farmland in 2017, representing 12% of the country's total farmland (Bloomberg 2017).

The accumulation of microplastics, arising from the deterioration of PEMs in fields, pose a significant threat to long-term soil health (Brodhagen et al 2017; Cao 2011; Jiang et al 1998; Yan et al 2006), water quality, and the delicate balance of marine ecosystems. PEMs, a common choice, lack degradability but deteriorate under UV radiation, necessitating single season use (Miles et al 2012; Wang et al 2020). Recycling PEMs is often cost-prohibitive due to collection, sorting, cleaning, and transportation (Cameron and Dudek 2009; Goldberger, et al 2019; Velandia, et al 2020b). Additionally, burning used PEMs is typically illegal due to environmental concerns (Russo et al 2004). Consequently, landfill disposal remains a common practice in the U.S. (Goldberger et al 2019; Madrid et al. 2022a). However, as PEMs deteriorate in landfills, microplastics are released, further contaminating terrestrial soil and water, as well as threatening fish and wildlife.

Soil-biodegradable plastic mulches (BDMs), have emerged as a promising solution, offering a more environmentally friendly approach to managing agricultural plastic mulch waste. However, to assure BDM films are an economic viable alternative, several challenges must be overcome. BDMs incur an often-higher cost compared to their conventional counterparts, PEMs, presenting a significant barrier to their widespread implementation. Furthermore, unreliable degradation rates of new BDM products during the production season can influence their efficacy in critical agricultural functions such as weed suppression and moisture retention, potentially impacting crop yields. The inherent uncertainty surrounding the degradation process and its susceptibility to environmental fluctuations further complicates the decision-making process for farmers and policymakers (Madrid et al 2022b).

The intricate trade-off between the environmental benefit of BDMs and their performance in agricultural production underscores the need for a more comprehensive economic evaluation. The resolution of this complex problem can help foster the adoption of sustainable agricultural practices and mitigate the global plastic pollution issue.

To capture the accumulation of plastic pollutants over time, this study utilizes a dynamic model, which offers a more complete understanding of intertemporal environmental interactions compared to static models that assume a level of pollutant unchanged by time. Dynamic models effectively capture the evolution of pollutant stocks, accounting for both the natural degradation of pollutants and the addition of new pollutants through emissions (Tietenberg 2004)[2].

Literature review

The detrimental effects of microplastic pollution in both aquatic and terrestrial ecosystems have been extensively documented (Eriksen et al 2013; Free et al 2014; Horton et al 2017;

[1]Mulch is a layer of material for plant protection and weed control. It also enhances crop growth by optimizing soil temperature and moisture. It is spread on the top of the soil (USDA 2012).

[2]Pollutants for which the environment has little or no absorptive capacity and that accumulate over time are called stock pollutants, including nonbiodegradable bottles tossed by the roadside (Tietenberg 2004).

Mason et al 2016; Nizzetto et al. 2016; Rochman 2018). Defined as plastic particles less than 5mm in diameter, microplastics pose a significant threat due to their invisibility compared to larger debris and their extremely slow degradation rate. Unlike organic matter, microplastics rarely decompose into harmless compounds like CO_2 or H_2O, instead accumulating persistently in the environment (Andrady 2011).[3] This accumulation poses a risk to aquatic and terrestrial wildlife, with documented cases of injury or mortality in birds, fish, turtles, invertebrates, and mammals through suffocation or poisoning by toxic chemicals, many of which are associated with cancer (Baldwin et al. 2016). Furthermore, Horton et al. (2017) estimate that 80% of microplastics found in oceans originate from freshwater sources, highlighting the critical role of terrestrial pollution pathways. Agricultural activities, particularly runoff and improper land management practices, contribute significantly to microplastic contamination in soil (Steinmetz et al 2016), ultimately impacting the marine environment. This concern aligns with the 2000 National Water Quality Inventory by the United State Environmental Protection Agency (2000), which identified agricultural nonpoint source pollution as the leading threat to US water quality. To address the pressing issue of microplastic pollution, this study examines the trade-off between the environmental benefits of BDMs and their potentially lower performance in agricultural production, aiming to comprehensively evaluate this trade-off from an economic standpoint.

Soil-biodegradable plastics have emerged as a potentially competitive alternative to conventional plastics, offering a more sustainable solution to mitigating agricultural plastic waste and pollution. These plastics are derived from biobased feedstocks or a combination of biobased and fossil fuel sources (Miles and Ghimire 2020). They degrade biologically under anaerobic or aerobic conditions, ultimately breaking down into harmless byproducts like carbon dioxide, water, and minerals (Avérous and Halley 2014). Recent advancements in soil-biodegradable plastics technology have improved their performance in agricultural applications (Ghimire et al 2018; Mohanty et al 2000; Sintim et al 2019; Tofanelli & Wortman, 2020).

Despite their environmental benefits, several challenges impede the widespread adoption of BDMs as a full replacement for PEMs in agriculture. The higher cost of BDMs compared to PEMs poses a significant economic challenge for farmers (Velandia et al 2018; Velandia et al 2020 c ; Marí et al 2019). Additionally, the degradation rate of BDMs can influence their effectiveness in weed suppression and moisture conservation, potentially impacting crop yields (Griffin-LaHue et al 2022; Li et al 2014). The uncertainty surrounding the degradation process and its environmental dependence (e.g., the moisture and the temperature level) further complicates the decision-making process for farmers.

Previous studies on BDMs have revealed both potential benefits and challenges, directly relating to our research questions of understanding and optimizing the balance between the environmental benefits and agricultural performance of BDMs. Sintim et al. (2019) and Sintim and Flury (2017) demonstrated the short-term viability of BDMs as an alternative to polyethylene in agricultural production but emphasized the need for further research on their long-term impact on soil health. This highlights the need for a comprehensive economic evaluation that considers both the immediate and long-term consequences of BDM use, as emphasized in our research question. Dentzman and Goldberger (2020),

[3]It has been correctly pointed out that plastic pollution could arise from a range of large fragments to microplastics to Nano-plastics. We articulate the problem in terms of microplastic pollution for the current paper, choosing to focus on the rate of degradation from conventional plastics to biodegradable plastics. Nevertheless, we point out that the fundamental dynamic economic framework introduced in this paper to model stock pollutants remains appropriate across a range of plastic fragments.

Goldberger et al. (2019), and Velandia et al. (2020c) identified farmer awareness of PEM waste management costs but hesitation to adopt BDMs due to their higher price and uncertainty about their financial and soil quality benefits. Conversely, Chen et al. (2020, 2019) found that growers are willing to pay a premium for BDMs if they result in higher crop prices and slower soil quality decline, and that consumers may also pay a premium for crops grown with BDMs. These findings on farmer acceptance and willingness to pay for BDMs highlight the importance of incorporating farmer preferences and economic incentives into the analysis, as the adoption of sustainable agricultural practices depends on the economic viability of BDMs for farmers. Velandia et al. (2020a, 2018) suggested that the high labor cost of removing and disposing of PEM waste could incentivize BDM adoption.

Despite these findings, a critical gap remains in understanding the dynamic nature and long-term economic and environmental consequences of microplastic accumulation from both conventional and biodegradable mulches. As Bishop (1993) noted, understanding these consequences, efficiency in particular, is necessary for developing sustainable farming and disposal practices. This is particularly important given concerns about the potential for soil to act as a sink for microplastics (Rillig 2012; Rochman 2018), raising questions about the long-term productivity and economic viability of agricultural systems. This gap in the literature underscores the need for a comprehensive economic evaluation of the trade-off between the environmental benefits of BDMs and their performance in agricultural production, which can help foster the adoption of sustainable agricultural practices and mitigate the global plastic pollution issue.

Therefore, this paper aims to fill this gap by developing a dynamic optimal choice model that considers the trade-off between the degradation rate of plastic mulches and their functionality in agricultural production. By incorporating the costs of plastic residue and disposal, as well as the long-term impact of microplastic accumulation on soil health, this stock pollutant model will provide a comprehensive framework for evaluating the economic and environmental implications of PEMs and BDMs use. The research will also explore the influence of various factors, such as disposal costs, crop prices, BDM certification and corrective tax, on decision-making regarding BDMs adoption and use.

While static models have informed the analysis of agricultural pollution control policies, dynamic models offer a more nuanced understanding of intertemporal environmental management, particularly for pollutants that accumulate over time. Static models inherently assume a constant level of pollutants, a limitation acknowledged in previous works (Braden et al 1989; Griffin and Bromley 1982; Innes 2000; Jacobs and Timmons 1974). In contrast, dynamic models, exemplified by the work of Conrad and Clark (1987) and applied to nitrogen control (Martínez and Albiac 2004) and pesticide mitigation (Anderson et al 1985; Conrad and Olson 1992), capture the fundamental concept of pollutant stock evolution in agricultural systems. These models recognize the natural degradation of pollutant stocks over time, alongside the addition of new pollutants through emissions. This concept extends beyond agriculture, as demonstrated in studies of aggregated polluters (Germain et al 2006; Jørgensen and Zaccour 2001). Our framework builds on this literature, applies an intertemporal approach to evaluate plastic mulch pollution and uses computational methodology to simulate an illustrative numerical example to understand the impact of incentives.

Dynamic models

Following previous studies in agricultural pollution control (Anderson et al 1985; Conrad and Olson 1992; Conrad and Clark 1987; Martínez and Albiac 2004), we develop a dynamic optimal control model for a representative grower. The private grower model analyzes the optimal degradation rate of plastic mulches, plastic residue management, and disposal decisions. Next, we introduce biodegradation standards and then extend the private grower model to a social planner model with an optimal corrective tax.

Private grower optimization

Consider N identical growers who use one type of plastic mulch in growing a single crop on a homogeneous farm under an infinite planning horizon. Initially each representative grower has perfect information of the degradation rate of mulches, and each grower is indexed by i. We assume that the market can offer different types of plastic mulches characterized by an in-soil degradation rate, $\delta_{i,t}$ where the degradation rate parameter $\delta_{i,t}$ is assumed to be between 0% and 100% $(0 \leq {}_{i,t} \leq 1)$.[4] The degradation rate equal to 0% represents the PEMs that have no degradation during a crop year t. If the in-soil degradation rate is greater than 0% but no more than 100% $(0 < \delta_{i,t} \leq 1)$, the plastic mulch is identified as a BDM. When the degradation rate is equal to 100%, it implies the completely degradable BDMs. Because of environmental differences for degradation rates in-soil as opposed to above the soil, the above-soil degradation rate is denoted as $\xi_{i,t} = \theta_{i,t}^{-1}(\delta_{i,t})$. Then the function $\delta_{i,t} = \theta(\xi_{i,t})$ expresses the in-soil degradation rate as a function of above-soil degradation rate. We assume the above-soil degradation rate is a monotone function of $\delta_{i,t}$, and the value of $\xi_{i,t}, \ = \theta_{i,t}^{-1}(.)$ is between 0% and 100% as well.[5] No matter the type of plastic mulches used by the farmer, the waste management decision on disposal of used plastic mulches will affect the plastic stock of pollution in the farmland soil. Henceforth, to focus the analysis, we assume if the farmer does not dispose of the plastic mulch waste after the growing season, then the used plastic mulches will be incorporated in the soil contributing to the plastic pollutant stock in the farmland soil, $S_{i,t}$.[6]

We assume the production function for each grower, i, $Q(\xi_{i,t}; S_{i,t}) = Q(\theta^{-1}(\delta_{it}); S_{i,t})$, is a continuously differentiable strictly decreasing function of the degradation rate, δ_{it} and the plastic pollutant stock in the farmland soil, $S_{i,t}$, $(Q_\delta < 0, Q_S < 0)$.[7] The production function $Q(.)$ is strictly concave $(Q_{\delta\delta} < 0,\ Q_{SS} < 0,\ Q_{S\delta} = 0,)$. The grower i is assumed to sell all the crops at the market price, P_t. Hence, $P_t Q(\theta^{-1}(\delta_{it}); S_{i,t})$ represents the revenue of

[4]Herein the term plastic mulch refers to both PEMs and BDMs with the degradation rate being the differentiating characteristic. Mathematically, and to be more formal, it is possible to bound the degradation rate away from zero. Here, we could choose some lower bound of the degradation rate, d0, that is very small and close to zero such the degradation rate is contained in a closed interval bound [d0,1] away from zero on the lower end and by 1 on the upper end, and then continue on with the optimization. Here, d0, would represent PEMs and (d0,1] represent BDMs.

[5]It has been pointed out that degradation and deterioration of plastic are not identical processes. We acknowledge this, but to retain the focus of the paper, recommend it as future research.

[6]Historically, across the world, farmers have tended to plow the plastic mulch back into the soil (Gao et al 2019), dispose of the used mulches in landfills, stockpile the plastic on site, bury it on side, or burn it (Sarpong et al 2024). Open burning it is illegal in many states, including Washington the location of the case study for this paper. Like landfills, stockpiling or burying it on site can lead to plastic residuals in the soil with long-term environmental consequences (Sarpong et al 2024).

[7]The production function is initially specified in terms of the above-soil degradation rate, as that drives the productivity increases from plastic mulches. To facilitate the analysis and reduce dimensions of the model, we express the above-soil degradation rate in terms of the in-soil degradation rate. This leads to a more parsimonious model, while retaining the main focus of the analysis. Henceforth, the degradation rate will refer to the in-soil degradation rate unless otherwise noted. Throughout the paper, subscripts denote partial derivatives, for example, $Q_\delta = \partial Q(\theta^{-1}(\delta_{it}); S_{i,t})/\partial\delta$, $Q_S = \partial Q(\theta^{-1}(\delta_{it}); S_{i,t})/\partial S$

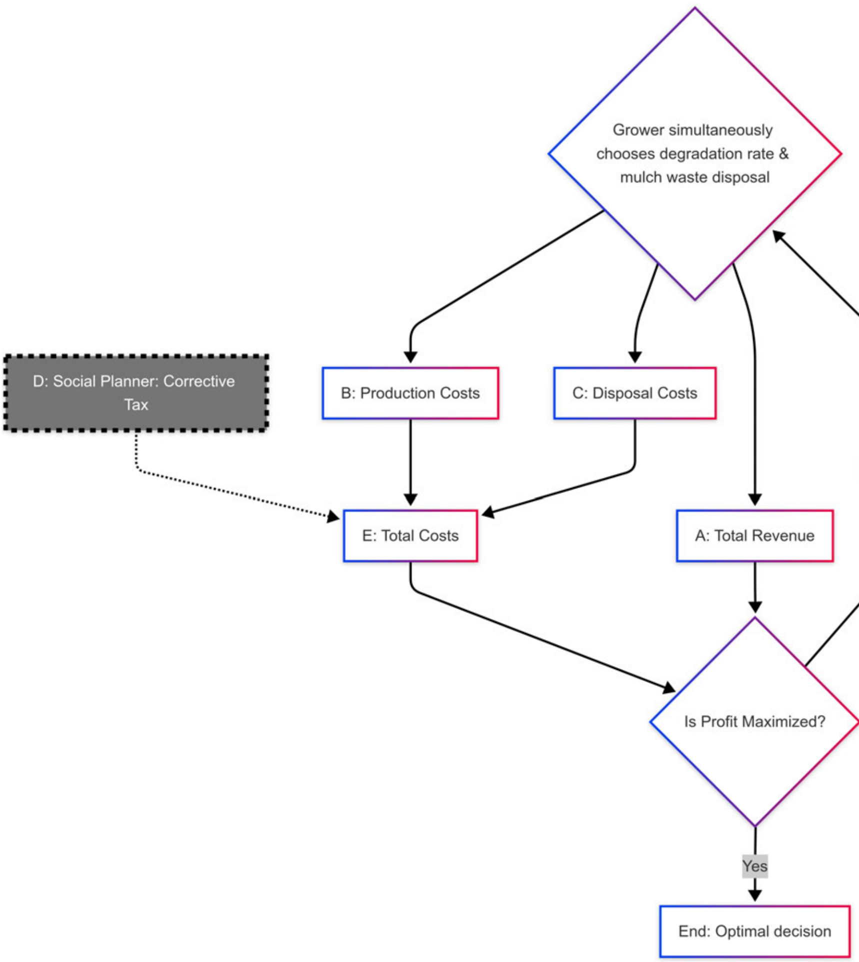

Figure 1. Grower decision-making flow chart[9].

grower *i*'s farm at the end of the crop year. Figure 1 illustrates a grower's decision flowchart, and box A is corresponding to the revenue.

The cost function has two components, the production costs and the disposal costs. The grower's private input cost function, $C(\delta_{i,t})$, is a strictly increasing function of the degradation rate ($C_\delta > 0$) to recognize that the cost of BDMs is higher than that of PEMs. The input cost function is non-concave ($C_{\delta\delta} \geq 0$). The production costs are represented by box B in Figure 1. The term $wh_t(\theta_{it}^{-1}(\delta_{it}), z_{it})$ represents the plastic-mulch-waste disposal cost, where w (measured in \$/lb) is the disposal rate.[8] $h_t(\theta_{it}^{-1}(\delta_{it}), z_{it})$ is the amount of plastic mulch waste disposed at disposal facilities (measured in pounds), where

[8]w (\$/lb) is equal to the used mulch disposal fee (\$/lb) plus labor cost of removing used mulch (\$/lb).

[9]For Box D, if a social planner aims to limit plastic waste pollution from growers, they may implement taxation. Growers, in turn, account for taxes when making profit-maximizing decisions. Section "Social planner optimization" details the social planner's problem.

$h_t(.)$ is a non-decreasing function of the portion of plastic mulch waste, z_{it}, handled by the disposal facility ($h_z \geq 0$), but a strictly decreasing function of the degradation rate ($h_\delta < 0$). It is non-concave ($h_{\delta\delta} \geq 0$) in the degradation rate. The disposal costs are represented by box C in Figure 1.

Following previous literature, the discount factor $0 < \rho < 1$ indicates that the grower values the current profit more than the future profit (Conrad and Olson 1992; Martínez and Albiac 2004). Therefore, the grower's objective of maximizing the discounted sum of current and future annual profits from selling a single crop is specified as

$$Max_{\{\delta_{it}, z_{it}\}} \pi(\delta_{it}, z_{it}; S_{it}, w)$$

$$= Max_{\{\delta_{it}, z_{it}\}} \sum_{t=0}^{\infty} \rho^t \left[P_t Q_{it}\left(\theta_{it}^{-1}(\delta_{it}); S_{it}\right) - C_{it}(\delta_{it}) - wh_t\left(\theta_{it}^{-1}(\delta_{it}), z_{it}\right) \right] \quad (1)$$

Subject to

$$S_{it+1} = G_{it}\left(\delta_{it}, z_{it}; S_{it}, w, \overline{S_{base,\,t}}\right) \quad (2)$$

$$0 \leq \delta_{it} \leq 1 \quad (3)$$

$$z_{it} = 0 \; or \; 1 \quad (4)$$

$$S_0 = \bar{S} \; and \; h_t \geq 0 \quad (5)$$

where the grower i simultaneously chooses a mulch with degradation rate, δ_{it} for the local environment, and the portion of plastic mulch waste handled by the disposal facility, z_{it}, which can have a value between 0 and 1. In practice most growers either dispose of all ($z_{it} = 1$) or none ($z_{it} = 0$) of the plastic mulch waste, which form individual corner solutions.[10]

Equation 2 is the function of the evolution for the plastic pollutant stock in the farm soil. At the end of each crop year, the plastic pollutant stock in the farm soil, $S_{i,t+1}$, will come from two sources: the plastic pollutant stock in the farmland soil from previous crop years and the in-flow of undisposed plastic mulch residue from the current crop year. At the beginning of the crop year, the farmland soil has contained plastic pollutant stock, S_{it}, but during the crop year, S_{it} degrades in the soil with a degradation rate, δ_{it}. Therefore, $G_{it}(.)$ is an increasing function of the plastic pollutant stock, $S_{it}(0 \leq G_s \leq 1)$, but a decreasing function of the in-soil degradation rate, δ_{it}. $\overline{S_{base,\,t}}$ is a base level of residue from PEM (or BDM for that matter) whether the mulch goes to a landfill or stays on the property. We also assume that if the completely degradable BDMs are used, the accumulated plastic mulch pollutant stock will equal to a base level, $\overline{S_{base,\,t}}$. We assume $G_{it}(.)$ is subject to the curvature conditions: $G_{\delta\delta} \geq 0, G_{ss} \geq 0 \; and \; G_{s\delta} \leq 0$.

The discrete current value Hamiltonian (Shone 2003) is

$$H = P_t Q_{it}(.) - C_{it}(.) - wh_t(.) + \rho\lambda_{i,t+1}(G_{it}(.) - S_{it}) \quad (6)$$

where $\lambda_{i,t+1}$ can be interpreted as the shadow price whose value is negative. The shadow price measures the loss in future profit due to additional plastic pollutant stock in the farmland soil reducing the soil productivity. The Karush-Kuhn-Tucker conditions (equations 7 - 10) and the sufficient transversality condition (equation 11) are as follows:

[10]This simplification reduces the complexity of the solution, while retaining the main features of the model that are the focus of the study. A study of fruit and vegetable growers in Tennessee, reported that 75% of the used plastic mulch went to landfills, and only 15% of the farmers used more than one disposal method (Sarpong et al 2024).

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$$\frac{\partial H}{\partial \delta} = P_{t\delta} - C_\delta - wh_\delta + \rho\lambda_{i,t+1}G_\delta > 0 \;\; yields \Rightarrow \;\; \delta^*_{it} = 1$$

$$\frac{\partial H}{\partial \delta} = P_t Q_\delta - C_\delta - wh_\delta + \rho\lambda_{i,t+1}G_\delta < 0 \;\; yields \Rightarrow \;\; \delta^*_{it} = 0 \tag{7}$$

$$\frac{\partial H}{\partial \delta} = P_t Q_\delta - C_\delta - wh_\delta + \rho\lambda_{i,t+1}G_\delta = 0 \;\; yields \Rightarrow \;\; 0 < \delta^*_{it} < 1$$

$$\frac{\partial H}{\partial z} = -wh_z + \rho\lambda_{i,t+1}G_z < 0 \;\; yields \Rightarrow \;\; z^*_{it} = 0 \tag{8}$$

$$\frac{\partial H}{\partial z} = -h_z + \rho\lambda_{i,t+1}G_z > 0 \;\; yields \Rightarrow \;\; z^*_{it} = 1$$

[11]

$$\frac{\partial}{\partial S} = P_t Q_S + \rho\lambda_{i,t+1}(G_S - 1) = -\rho\lambda_{i,t+1} + \lambda_{i,t} \tag{9}$$

$$\frac{\partial H}{\partial \rho\lambda_{i,t+1}} = G_{it}\left(\delta_{it}, z_{it}; S_{it}, w, \overline{S_{base,\,t}}\right) - S_{it} \geq 0 \tag{10}$$

$$\rho^t \lambda_{i,t} S_{i,t} = 0 \tag{11}$$

We use λ^*, δ^*, S^*, and z^* to denote the steady-state solutions. Condition (8) quantifies the differences between the marginal cost ($-wh_z$) and marginal benefit ($-\rho\lambda_{i,t+1}G_z$) associated with the disposal decision. Both the cost and benefit of disposal are not associated with crop production function or crop price. If the marginal cost is large than the marginal benefit of disposing mulch waste, i.e., $-wh_z + \rho\lambda_{i,t+1}G_z < 0$, the grower will till all used plastic mulches into the farmland soil. This practice leads to a continuous accumulation of plastic pollutants, diminishing soil productivity and ultimately causing the grower to cease farming operations. Consequently, the model will converge towards the transversality condition (11). An increase in disposal costs and fees, w, will elevate the marginal cost of disposing mulch waste, making condition $-wh_z + \rho\lambda_{i,t+1}G_z < 0$ more likely to be satisfied. Therefore, the grower is more inclined to till all used plastic mulches into the soil.

However, if the marginal cost is smaller than the marginal benefit of disposing mulch waste, i.e., $-wh_z + \rho\lambda_{i,t+1}G_z > 0$ the grower will opt to send all used plastic mulches to a disposal facility. In this case, the plastic pollutant stock in the farmland soil is determined by an accumulated base level of residue from mulch even if it goes to a disposal facility.

Considering condition (7) that identifies the degradation rate decision, we first discuss the boundary solutions. Suppose that $P_t Q_\delta - C_\delta - wh_\delta + \rho\lambda_{i,t+1}G_\delta > 0$, then the optimal in-soil degradation rate $\delta^* = 1$ (the fully degradable BDMs). Therefore, if z^*_{it} is equal to 0, the optimal pollutant stock in the farmland soil S^*will only be determined by initial plastic residue in the farmland soil. Considering the case in which

[11]We assume that an interior solution never occurs, since we assume growers will either send all plastic waste to the disposal facility or leave all plastic waste on the farmland, which indicates corner solutions. This allows us to compare and contrast the landfill disposal scenario to the tilling in scenario across all levels of BDM degradation rates. Note that uncertainty exists in that some products labeled biodegradable do not fully degrade relative to industry standards (Brodhagen et al 2017).

$P_tQ_\delta - C_\delta - wh_\delta + \rho\lambda_{i,t+1}G_\delta < 0$, we obtain that the optimal in-soil degradation rate $\delta^* = 0$, which is the conventional PEMs.

We now turn to the interior solution, where $0 < \delta^*_{it} < 1$. We follow Schnitkey and Miranda (1993) to drop the time subscript *t,* and grower subscript *i*, and denote the steady state for a representative grower as $\lambda^*, \delta^*, S^*, z^*$. Therefore, the optimal degradation rate at the steady state satisfies the equation (12) (see derivation is in Appendix A)

$$\delta^* = \Psi^{-1}\left(\frac{C_\delta + \mathrm{w}h_\delta}{\bar{P}}\right) \tag{12}$$

where $\Psi^{-1}(.)$ is the inverse function of $\Psi(.)$ with respect to the degradation rate, and it is a strictly decreasing function of $\frac{(C_\delta + wh_\delta)}{\bar{P}}$. Equation (12) identifies the steady-state degradation responses relative to changes in key parameters. Consequently, when the crop price, $\bar{P}$, increases, the grower is more likely to use plastic mulches with a higher degradation rate. In other words, when crop prices are higher, farmers have the financial incentive to prioritize long-term soil improvement by choosing the faster-degrading mulch with higher upfront cost. Equation (12) also predicts that for a higher the disposal rate and fee, *w*, then a mulch with a higher degradation rate will be chosen by the grower.[12] If disposal fees for plastic mulch are very high in the farmer's area, the economic benefits of faster degradation could outweigh other considerations. A higher degradation rate means less plastic to haul away and pay for at the end of the season. Essentially, the analysis of equation (12) reveals that higher crop prices or higher disposal cost incentivize growers to invest in practices that maximize long-term yield and minimize costs. Growers will weigh the benefits of faster degradation (reduced disposal costs and soil health) against the potentially higher upfront cost of BDMs. The relationship revealed in this research aligns with existing research on the private interest of farmers in maintaining or increasing soil quality. Note that Issanchou et al. (2019) reported that crop prices positively influence farmer investments in soil conservation.

Biodegradation standards

In this section, we relax the assumption of perfect information regarding degradation rate. Here, growers rely on biodegradation standards and certifications to identify biodegradable plastic mulches. Plastic producers substantiate degradability claims by adhering to national or international standards (Federal Trade Commission 2012, 2014). Several standards guide the identification of biodegradable plastics in various environments (compost, marine, etc.): ASTM D6400 and D5526-11 (US), EN 13432 and EN 17033 (Europe/Japan), and ISO 17088. These standards establish protocols, materials, and conditions for testing, as well as define degradation rate benchmarks for certified soil-biodegradable plastics. For instance, ASTM D6400 certifies a plastic as soil-biodegradable if at least 90% of its organic carbon converts to CO_2 within 180 days under controlled laboratory conditions (Avérous and Halley 2014).

In other words, asymmetric information creates a challenge for BDMs production. When farmers lack complete knowledge of BDMs' degradation rate, BDMs manufactures are required to produce BDMs meeting the standard, the variety of plastic mulches offered with varying degradation rates may be lower compared to a scenario with perfect information. To reflect such conditions, the constraint (3) will be modified as follows:

[12] $h_\delta < 0$, so when $\bar{w}$ increases, $(C_\delta + wh_\delta)/\bar{P}$ decreases.

$$\delta_{it} = 0 \ \ or \ \ 0.9 \le \delta_{it} \le 1 \tag{13}$$

Let δ^C denote the optimal degradation rate under the current biodegradation certification scheme. If δ^* defined in equation (13) is no smaller than 90% ($\delta^* \ge 0.9$), $\delta^C = \delta^*$. However, if $\delta^* < 0.9$, then the optimal choice will depend on the general shape of a grower's profit function.

Figure 2 depicts three plausible scenarios. Figure 2(a) depicts the scenario that the lifetime profit is larger when a grower chooses PEMs rather than BDMs meeting standards. A grower would gain a higher lifetime profit by using BDMs meeting standards with a 90% degradation rate than PEMs if the scenario represented in Figure 2(b) happened. We also can observe the situation depicted in Figure 2(c) where there is no difference between using PEMs or BDMs meeting standards with a 90% degradation rate to achieve the highest lifetime profit. Simulation methods are applied in section "Empirical model and data" to characterize the shape of a grower's profit function so that we are able to study the grower's optimal choice under current biodegradation standards in section "Results and discussion."

Social planner optimization

This section expands our model to consider the social optimum and the policy implications of aligning individual grower decisions with the social planner's choice (assuming perfect information).

While growers manage plastic mulch waste on-farm to minimize reductions in crop productivity from soil pollution, negative environmental externalities still persist. Landfilling, a common disposal method, contributes to the global plastic waste crisis, harming terrestrial (Dreyer et al 1999; Lgbokwe et al 2003; Omidi et al 2012) and marine animals (Cameron and Dudek 2009; Derraik 2002; Joyner and Frew 1991). Incineration releases greenhouse gases by converting petroleum-based carbon into atmospheric carbon (Ellis et al 2005; Gautam 2009).

To mitigate negative externalities arising from pollution, social planners can employ various environmental policies. Three primary instruments exist for pollution control, aiming to achieve a socially optimal outcome (Baumol and Oates 1988; Kolstad 2011). Command-and-control regulations directly limit pollution emissions or mandate specific technologies. While offering certainty in pollution reduction and potentially simplifying complex environmental processes, this approach can discourage innovation in pollution control methods (Kolstad 2011). Pollution fees (or taxes) incentivize polluters to internalize external costs by imposing a charge on their emissions (Pigou 1932). Pollution permits utilize a market-based approach where a limited number of permits are issued and traded among firms. Both fees and permits are price-based incentives that require less information than command-and-control and can be cost-effective due to market-driven adjustments. However, these price-based instruments may struggle to address the complexities of environmental systems without becoming overly complicated themselves (Kolstad 2011) and may face challenges in accurately measuring marginal social damage (Baumol and Oates 1971).

Consequently, many scholars advocate for a hybrid approach that combines the strengths of both quantity-based and price-based instruments (Baumol and Oates 1971; Jacobs and Timmons 1974; Moffitt et al. 1978; Schnitkey and Miranda 1993; Holland 2012). This typically involves setting a cap on total pollution allowed and using a market mechanism (such as a tax or a tradable permit system with a price ceiling) to ensure the cap

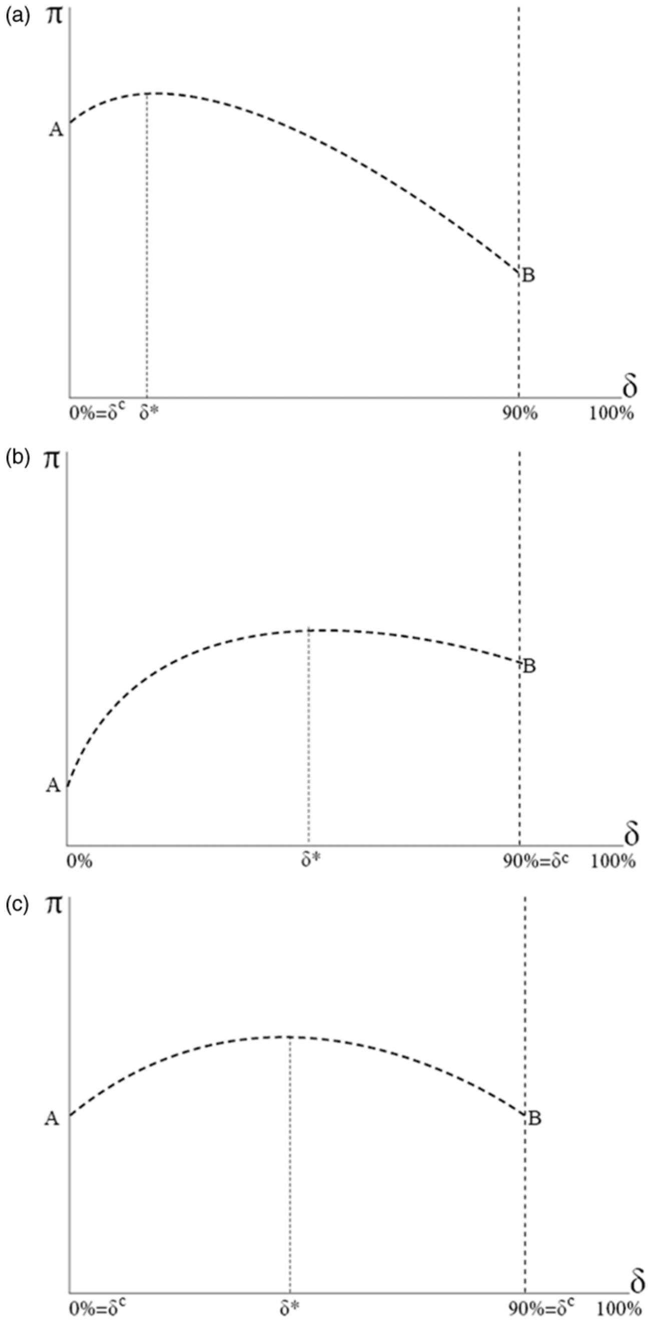

Figure 2. Lifetime profits comparison between using PEMs and using BDMs meeting standards.a). PEMs is optimum b). BDMs meeting standards is optimum c). Both PEMs and BDMs meeting standards are optimum. Note: both point A and B achieve a local optimum. To obtain the global optimum, we need to compare the profit at point A and B, and the one having higher profit will be the global optimum.

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is not exceeded. This approach allows policymakers to achieve emission reduction targets while encouraging innovation in pollution control.

Therefore, we adopt the hybrid approach in this research and assume that the social planner aims to control both plastic pollutant stock in farmland and waste disposed of in landfill facilities with a limitation. Such a limitation can be expressed as an extra constraint for the optimization problem

$$\sum_{i=1}^{N} S_{it} + \sum_{i=1}^{N} h_{it} \le \overline{D_t} \tag{14}$$

where the maximum level of the plastic mulch waste is exogenously determined by the social planner as $\overline{D_t}$.

The socially optimal problem is to maximize the summation of all growers' profit in equation (15) subject to conditions (2) to (5) and constraint (14)

$$W = \sum_{i=1}^{N} \sum_{t=0}^{\infty} \rho^t \left[P_t Q_{it}\left(\theta^{-1}(\delta_{it}), S_{it}\right) - C_{it}(\delta_{it}) - wh_t\left(\theta_{it}^{-1}(\delta_{it}), z_{it}\right) \right] \tag{15}$$

Therefore, the discrete current value Hamiltonian is as follows:

$$\sum_{i=1}^{N} \left[P_t Q_{it}(.) - C_{it}(.) - wh_t(.) + \rho\lambda_{i,t+1}(G_{it}(.) - S_{it}) \right] - \tau_{i,t} \left[\sum_{i=1}^{N} S_{it} + \sum_{i=1}^{N} h_{it} - \overline{D_t} \right] \tag{16}$$

where $\tau_{i,t}$ is the shadow price associated with the plastic mulch waste constraint (14), which represents the minimum monetary incentive the social planner has to impose on grower i so that the total amount of plastic mulch pollution in the farmland soil (S_{it}) and the plastic waste sent to disposal facilities (h_{it}) from all growers, N, will not be over the limit $\overline{D_t}$. Therefore, $\tau_{i,t}$ can be considered as a corrective tax. By solving the first-order conditions of discrete current value Hamiltonian, if the constraint (14) is binding, we find that the optimal corrective tax is defined as

$$\tau^w = \frac{\bar{\mathrm{P}}\Psi(.) - C_\delta - \mathrm{w}h_\delta}{h_\delta} \tag{17}$$

Note that if the plastic mulch waste generated by all growers are less than the limit, $\sum_{i=1}^{N} S_{it} + \sum_{i=1}^{N} h_{it} < \overline{D_t}$, the optimal corrective tax is $\tau^w = 0$. Since the models for the individual grower and social planner cannot be completely solved analytically, we turn to simulation methods to solve for the optimal solutions to the models. Figure 1, Box D illustrates that once the social planner determines the corrective tax amount, growers will incorporate the tax into their decision-making, internalizing the social cost of plastic pollution and considering both farmland and landfill impacts. The numerical methods and results are discussed in sections "Empirical model and data, Results and discussion."

Empirical model and data

In this section, we introduce an empirical economic model of plastic residue in farmland soil, which is more likely than the theoretical model to capture the complexities intrinsic to real-world economic behavior. First, a deterministic model and then a stochastic extension of the model are presented in the Appendix C. Then, data for a case study application in tomato production in the state of Washington are discussed.

Illustrative case study: deterministic environment

Grounded in the optimization specification and Karush-Kuhn-Tucker equations (1)-(11), and following Schnitkey and Miranda (1993) and Miranda and Fackler (2004), we apply the functional forms:

$$Q_{it} = \alpha_0 - \alpha_1\delta_{it} - \alpha_2 S_{it} - \frac{1}{2}\alpha_{11}\delta_{it}^2 - \frac{1}{2}\alpha_{22}S_{it}^2 \tag{18}$$

$$h_{it} = \beta_1 z_{it} - \beta_{12}\delta_{it}z_{it} \tag{19}$$

$$C_{it} = v_0 + v_1\delta_{it} \tag{20}$$

$$G_{it} = \eta_0 - \eta_1\delta_{it} + \eta_2 S_{it} - \eta_3 z_{it} - \eta_{13}\delta_{it}z_{it} + \eta_4 \tag{21}$$

$$w = \tilde{w} * \varphi, \quad where \;\; \varphi = \chi_0 + \chi_1 z_{it}^* \tag{22}$$

The well-defined functions allow us to numerically illustrate the results. α_0 represents the crop production under the PEMs. The negative coefficients of the production function α_1 and α_{11} captures the impact of the changes in degradation rates on crop production. Meanwhile, negative coefficients α_2 and α_{22} measure the reduced crop production associated with the increased plastic residue in the farmland soil. The total amount of the plastic mulch used by grower i during period t is denoted as β_1. v_0 and η_0 mean the production cost not associated with the plastic mulch and the amount of plastic mulch residue in the farmland soil at the very beginning of period t, respectively. η_3 captures the impact of disposal decisions on the dynamic accumulation of plastic pollutant in the farmland soil. $\delta_{it}z_{it}$ reflects the interaction between the grower's disposal decision and the mulch's degradation rate, which may in turn affect the plastic pollutant in the farmland soil. η_4 represents a base level of residue from PEM (or BDM for that matter) whether the mulch goes to a landfill or stays on the farmland. w is the economic disposal cost, and it is determined by the disposal cost in monetary value, $\tilde{w}$, and the effort coefficient φ. φ is a function of the portion of mulches to be removed from the farmland, z_{it}^*. When near zero portion of mulches is to be removed, then the effort coefficient $\chi_0 > 0$. As the portion of mulch required to removed increases, the effort coefficient will increase with the rate of $\chi_1 > 0$. We use effort coefficient to capture the situation that as the grower seeks to remove more percentage of plastic mulch from the farmland to the landfill, the more effort they will put in, which increase the economic disposal cost.

We apply the collocation method to solve the current dynamic economic model (Bellomo et al 2007; Golub and Ortega 1992). Under the deterministic environment, we perform sensitivity analysis to examine how changes in key parameters affect the decision maker's optimal choice and the accumulation of plastic residue in the farmland soil. Results are presented in section "Results and discussion."

Data

This study focuses on tomato growers due to readily available data, their extensive use of mulch, and the significance of tomato production within specialty crops.[13] Tomatoes rank among the top three vegetables in the United States by area harvested and total production, contributing over 50% of the total vegetable category in 2019 (USDA-NASS 2020). Furthermore, their economic importance is undeniable, placing them among the top three vegetables in terms of value, alongside head lettuce and onion, accounting for 32% of the

[13]We also performed a simulation based on strawberry production. It is available upon request.

total vegetable production value in 2019 (USDA-NASS 2020). Additionally, mulch plays a critical role in tomato production. To simplify analysis, we assume a one-acre tomato farm and normalize all inputs and outputs on a per-acre basis. While this study focuses on Washington State tomato growers, the particular numerical values might not be directly applicable to a specific grower, as well as other crops or regions, due to differences in crop prices, labor costs, and disposal costs. However, the modeling framework with sensitivity analyses, such as examining the impact of landfill tipping fees and the influence of crop price changes on optimal choices, offer valuable insights that can be generalized to a broader context.

In the baseline analysis, average tomato prices are \$1.4/ lb, which is based on the northwestern US tomato retail price (USDA 2021).[14] The plastic waste disposal fee is assigned \$0.042/lb, which is based on the surveyed landfill tipping fee in Washington in 2018 (Environmental Research and Education Foundation 2018).[15] A field survey was also conducted to characterize tomato growers' plastic mulch choices in Washington by Mount Vernon Northwestern Washington Research and Extension Center's Specialty Crop Research Initiative (SCRI) project team from 2010 to 2012 (Galinato et al 2012). All the baseline parameter values are presented in Table 1, and we assume the discount factor ρ is equal to 0.9.[16] Piehl et al (2018) reported about 0.1 pounds of plastic residue per acre in German agricultural land, whereas Gao et al (2019) reported over 200 pounds of plastic residue per acre in China on lands that have had long-run exposure to plastic mulch use and its residue. Our baseline assumptions and initial conditions of plastic residue are more in line with Piehl et al (2018), meaning we do not impose in the baseline that the farmland has a history of long-run buildup of plastic residue in the soil.

Results and discussion

In this section, we derive economic insights from an illustrative empirical model of this economic system. The results are then examined through four lenses: optimal grower behavior under deterministic and stochastic environments, the impact of a corrective tax, the effectiveness of current BDM standards and the impact of growers' risk preferences. It is crucial to acknowledge that the model's findings presented below are contingent upon the underlying assumptions, data, and parameters employed. As such, they may not be universally applicable across all agricultural scenarios. Nonetheless, the derived outcomes, along with a selection of sensitivity analyses, offer valuable contributions to our understanding of economic behavior within this system and inform potential policy recommendations.

Optimal choice of a representative grower

We first discuss the optimal selection of a representative grower when offered a range of plastic mulches with varying degradation rates under deterministic environment, assuming the grower has perfect knowledge of these rates. Table 2 summarizes the

[14]In the state of Washington, tomatoes are predominately sold at farmer's market. Hence, the prices received are retail prices.

[15]\$83.44/ton is equal to \$0.042/lb

[16]let *dis* denote discount rate, the discount factor is calculated through $\rho = 1/(1 + dis.)$ We assume dis = 0.07, and the discount factor is approximately equal 0.9. For the past 20 years, the Office of Management and Budget (OMB) has advised federal agencies to use $dis = 0.07$ in policy analyses. 7 percent rate captures the return paid by private capital, reflecting effects on investment and business.

Table 1. Baseline coefficients of production, cost, disposal, and plastic residual evolution in a fresh-market tomato production system

Parameters	Name	Values (Tomato)
Production Function (lb)		
α_0	Crop production under PEMs	30,360[1]
α_1	Coefficient of production associated with degradation rate	1[2]
α_2	Coefficient of production associated with plastic residue	0.1[2]
α_{11}	Coefficient of production cost associated with degradation rate squared term	0.005[2]
α_{22}	Coefficient of production cost associated with plastic residue squared term	5[2]
Crop Price ($/lb)		
P_t	Tomato price	1.4
Production Cost ($)		
ν_0	Production Total Cost	28,785.02[1]
ν_1	Coefficient of production cost associated with degradation rate	10[3]
Disposed Plastic Mulch Waste (lb)		
β_1	Total amount of the used plastic mulch during period *t* by grower *i*	1197.9[1]
β_{12}	Coefficient of disposed plastic mulch associated with the interaction of the grower's disposal decision and the mulch's degradation rate	0.5[3]
χ_0	Effort coefficient when close to 0% mulches removed from the farmland	0.2[3]
χ_1	The parameter used to determine the effort coefficient increase rate as the portion of mulch removed from the farmland increases	0.8[3]
Plastic Residue in the Farmland Soil (lb)		
η_0	Initial plastic residue in the farmland soil	3.2[2,3]
η_1	Coefficient of plastic residue associated with degradation rate	0.5[3]
η_2	Coefficient of plastic residue associated with plastic pollutant	0.1[3]
η_3	Coefficient of plastic residue associated with the grower's disposal decision	3.2[3]
η_4	A base level of residue from PEM (or BDM for that matter) whether the mulch goes to a landfill	0.05[3]

(*Continued*)

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Table 1. (*Continued*)

Parameters	Name	Values (Tomato)
η_{13}	Coefficient of plastic residue associated with the interaction of the grower's disposal decision and the mulch's degradation rate	0.5[3]

[1]The following values of parameters are obtained from "2011 Cost of Producing Fresh Market Field-Grown Tomatoes in Western Washington."

α_0 representing the crop production under the PEMs is 30,360lb/acre.

β_1 denoting the total amount of the used plastic mulch used during period *t* by grower *i*. The parameter value is obtained from Galinato et al (2012).

v_0 representing the production cost not associated with the plastic mulch used by grower *i* is equal to $25,982.92. The production cost has been adjusted based on the agricultural price paid indexes in the USDA NASS Quickstats database. Machinery cost in 2019 is 24% higher than in 2011; and all other production items (commodities, services, interest, tax, wage rates) in 2019 is 10.5% higher than in 2011.

[2]Values are calibrated based on Galinato et al (2012) and Jiang et al (1998). The elasticity of soil plastic residue in affecting production is less than -0.028% when plastic pollutant levels are 3.2 lb. Following their work, we assume parameter values,$\alpha_1, \alpha_2, \alpha_{11}, \alpha_{22}$ that result in an elasticity of less than 0.028%. While there is no study quantifying the relationship between mulch degradation rate and cost, we assume parameter values, v_1, and conduct sensitivity analysis to check the robustness of the results.

[3]The remaining parameter values are assumed to satisfy the first-order conditions and the functional form assumptions in section "Private grower optimization." Due to the lack of empirical studies providing values for these parameters, we conduct sensitivity analysis using different parameter values to check the robustness of the results. This paper presents sensitivity analysis for key parameters; a complete sensitivity analysis is available upon request.

findings for the baseline scenario and several sensitivity analyses (increased crop prices, production costs, and yield impact from plastic residue). The baseline results in Table 2 indicate that growers will choose PEMs and dispose of all waste at a landfill facility. This approach leads to a long-term equilibrium of 0.06 lb plastic residue remaining in farmland soil, while plastic waste accumulates continuously at the landfill. However, the outcomes in Table 2 from increasing crop prices, production costs, and the negative impact of plastic residue on yield do not influence the growers' optimal choice from the baseline scenario. This aligns with our theoretical finding that altering parameters related to the production function or crop price does not directly influence growers' optimal disposal method choices (Equation (8)). As growers currently dispose of used mulch waste in landfills, plastic pollutants do not accumulate and harm farmland soil quality. Consequently, growers lack the incentive to adopt more expensive BDMs, leading to ongoing plastic waste accumulation at landfills.

Next, in Table 3, we examine the responses in the optimal choices and the accumulation of plastic waste to increases in landfill tipping fees.

Rising landfill tipping fees in the U.S. (Environmental Research and Education Foundation 2018; Repa 2005) incentivize grower adoption of BDMs. Projecting a 4.7% average annual growth rate from a baseline of $0.042/lb, Washington State's tipping fee could reach $0.052/lb ($104.98/ton) in five years, $0.066/lb ($132.08/ton) in ten years, and $0.105/lb ($209.08/ton) in twenty years. As demonstrated in section "Biodegradation standards," growers are more likely to till used mulch into farmland when disposal costs become sufficiently high. Our empirical model predicts a tipping point of $0.055/lb. Above this threshold, growers financially benefit from leaving used plastic mulches on-site or tilling them into the soil.

A comparative statics analysis (Table 3) reveals that if the tipping fee reaches $0.066/lb, $0.105/lb within ten years and twenty years respectively, growers transition from PEMs to BDMs with a 61% degradation rate (interior solution, condition 7), maximizing profit by favoring on-site decomposition (The alternative analysis based on dynamic path analysis is

Table 2. Optimal steady-state disposal method, degradation rate and accumulated plastic pollutant in the farmland soil[17]

	Disposal method	Degradation rate (δ_{it})	Plastic pollutant in the farmland soil (lb.) (S_{it})	Plastic pollutant in the landfill from the farm (lb.) ($h_t(.)$)
Grower Optimum (Baseline)	Disposal Facility	0%	0.06	∞
Crop price (P_t) raises 50%	Disposal Facility	0%	0.06	∞
The coefficient of production cost associated with degradation rate (ν_1) increases 50%	Disposal Facility	0%	0.06	∞
The coefficient of production measuring the reduction associated with the plastic residual in the farmland soil (α_{22}) rescaled to -500[1]	Disposal Facility	0%	0.06	∞

[1]Gao et al. (2019) reported that when the residual plastic mulch is over 214lb per acre, then the crop yield would have a significant decrease. To incorporate the results from this study, in our comparative statistics analysis, we rescaled the coefficient α_2 to -500 in order to have a production function that will have significant yield decreases at 214 lb of mulch residue.

in Appendix B). Consequently, BDM waste in farmland soil reaches an equilibrium of 3.27 lb, and plastic waste contributions to landfills are eliminated. Furthermore, with a higher tipping fee ($0.105/lb in 20 years) and more severe crop damage (Gao et al. 2019), growers adopt BDMs with a 100% degradation rate (boundary solution, condition 7). This incentivizes BDM adoption by discouraging landfill disposal, preventing soil quality reduction, and minimizing plastic pollution. Similar to Bueno and Valente (2019) and Fullerton and Kinnaman (1996), who found monetary incentives effective in inducing behavioral changes in household waste generation, we observe analogous results for growers facing rising landfill tipping fees.

Increased crop prices also incentivize faster BDM adoption. As Table 3 shows, a 7% crop price rise leads growers to adopt BDMs with faster degradation rates, prioritizing long-term soil improvement (condition 7). This aligns with our theoretical analysis, indicating that higher crop prices encourage the use of faster-degrading mulch despite higher upfront costs.

Even though this study focuses on Washington State tomato growers, the modeling framework with sensitivity analyses provide insights that can be generalized to a broader context. For example, the finding that increasing landfill tipping fees can incentivize the adoption of BDMs is relevant for policymakers in other regions seeking to promote sustainable agricultural practices. Similarly, the analysis of how crop price fluctuations affect BDM adoption decisions can inform growers and policymakers across different crops and regions.

[17]While our analysis applied a Monte Carlo simulation with up to 1,000 periods to identify the steady state, it converges to the steady state rapidly (see appendix for more details). Nevertheless, these results are conditional on the parameters and information applied in the current illustrative analysis, and should be updated with additional and new information in future research.

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Table 3. Analysis of the impact of landfill tipping fee

	Projected landfill tipping fee ($/lb) ($w$)	Disposal method	Degradation rate (δ_{it})	Plastic pollutant in the farmland soil (lb.) (S_{it})	Plastic pollutant in the landfill from the farm (lb.) ($h_t(.)$)
Threshold	0.055	Disposal facility/In soil	0%	0.06	∞
In 5 years	0.052	Disposal facility	0%	0.06	∞
In 10 years	0.066	In soil	61%	3.27	0
In 20 years	0.105	In soil	61%	3.27	0
In 20 years and α_{22} rescaled to -500	0.105	In soil	100%	3.06	0
In 20 years and Crop price raises 7%	0.105	In Soil	95%	3.08	0

Optimal choice of a representative grower with BDMs meeting standards

Table 4 presents the empirical results of optimal grower choice when the market offers either PEMs or BDMs meeting a minimum 90% degradation standard. Our analysis, constrained by a minimum 90% biodegradability requirement (Equation (13)), shows that growers maximize profit by choosing either PEMs or BDMs that meet this standard (Figure 2, Panels a and b). This is because a strictly interior optimum degradation rate is not achievable. To determine the best overall choice (global optimum), we compare profits across these two options, as presented in Table 4. While factors like tomato price do not change these optimal choices, they do affect the profitability of each, influencing the global optimum. We further examine the impact of rising tomato prices on this choice, with results detailed in Table 4.

Although Table 4 (illustrated in Figure 2c, Section "Dynamic models," points A and B) suggests minimal profit differences between PEMs and BDMs meeting the standard (less than 0.1%), it reveals important dynamics. Growers with low disposal costs tend to favor PEMs due to slightly higher profits. However, as disposal costs rise, on-site disposal becomes more appealing, making BDMs more competitive. For example, at a tomato price of $3/lb, growers using BDMs meeting the 90% degradation standard earn $117 more profit than those using PEMs[18]. This highlights the complex interplay between BDM certification, grower choices, and plastic accumulation.

Our analysis also shows that choosing BDMs with a 90% degradation rate caps total plastic mulch waste on farmland and in landfills at 3.06 lb/farm. In contrast, continued use

[18]The $117 profit difference between BDMs and PEMs may appear small, but it is significant in the context of low initial plastic residue levels. To further explore this, we increase the initial plastic residue parameter, η_0, from 3.2 lb to 40.2 lb, simulating a scenario with a history of medium-severity long-run buildup of plastic residue. With a crop price of $3/lb and a high landfill tipping fee, the profit incentive to adopt BDMs becomes substantial, with growers earning $3,135 more profit using BDMs instead of PEMs. This highlights the impact of pre-existing plastic pollution on the economic viability of BDMs.

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Table 4. Profit comparison between using PEMs and using BDMs meeting standards

		Disposing of plastic waste (Low Disposal Fee[3])			Leaving plastic waste on-site (High Disposal Fee[4])		
		Optimal Degradation Rate (δ_{it})			Optimal Degradation Rate (δ_{it})		
		PEMs 0%	BDMs 90%	Diff.	PEMs 0%	BDMs 90%	Diff.
Price of tomatoes (P_t)	$1/lb	**$15,271**[2]	$15,172	$99	**$15,459**[2]	$15,442	$17
	$2/lb	**$318,870**[2]	$318,763	$107	$318,769	**$318,813**[2]	$-44
	$3/lb	**$622,470**[2]	$622,354	$116	$622,078	**$622,195**[2]	$-117
Plastic Pollutant (S_{it})	Farmland soil	0.06 lb	0.06 lb		3.61 lb[1]	3.06 lb	
	Landfill from farm	∞	3.00 lb		0 lb	0 lb	

[1]It is an unstable steady state, and once it reaches 3.61 lb, a grower will stop farming, due to the reduction of production related to the mulch residual in farmland soil.
[2]The higher profit that is achieved by one of two local optima, and the corresponding local optimum is the global optimum.
[3]Low Disposal Fee used $0.04/lb
[4]High Disposal Fee used $0.6/lb.

of PEMs leads to either the continual buildup of plastic waste in landfills or the complete abandonment of farming due to the soil contamination (converging towards the transversality condition 11).

However, the economic incentive for adopting certified BDMs (with even higher degradation rates) is limited. Our analysis reveals that BDMs with a 90% degradation rate represent only a global profit maximum in 2 out of 6 scenarios. Therefore, certified BDMs with higher degradation rates, while environmentally preferable, may be less appealing to profit-driven growers. This finding aligns with research on other certification programs, such as organic certification and Fair-Trade coffee certification (Seufert et al., 2012; Dragusanu et al., 2014), which also highlight the potential trade-offs between achieving standards and maximizing profit.

Corrective tax

Besides the increasing landfill tipping fee in the long term, a corrective tax is another approach to reduce plastic mulch waste in both farmland soil and landfills. The results for the numerical analysis of a corrective tax (Equation 17) are represented in Table 5. The corrective tax, derived from the shadow price of the plastic waste constraint (Equation 14), internalizes the social cost of plastic pollution, incentivizing growers to adopt BDMs and reduce landfill disposal. This encourages a shift towards the socially optimal outcome with lower plastic waste in both farmland and landfills. The tax level is influenced by crop prices, production cost and waste management cost, balancing environmental goals with each grower's profit maximization goal.

We assume that the policy limiting plastic pollutants, $\boldsymbol{D}_t$ is 400 lbs. for a total of 130 one-acre-farm growers.[19] In contrast to the grower optimum in baseline presented in Table 2, Table 5 demonstrates that a corrective tax scheme targeting farm-discharged used mulch waste incentivizes growers to reduce total mulch waste pollution. This reduction is achieved through various means, including innovation in waste management practices. As Endres (2011) observed, firms may redesign production processes to mitigate pollution and avoid corrective taxes. Similarly, our findings indicate that growers, faced with a corrective tax, opt to retain mulch waste on the farm and transition from PEMs to BDMs with a 96% degradation rate. Within the model's assumptions, this choice leads to a long-term steady state with 3.08 lbs/farm of plastic pollutants remaining in the farmland soil and no plastic waste deposited in landfills. This finding complements those in section "Optimal choice of a representative grower," indicating that a corrective tax effectively encourages the adoption of BDMs that meet biodegradable standards.

Table 5 further illustrates that while decreased crop prices and increased production costs impose financial burdens on growers, the corrective tax increases in both scenarios. As shown in Table 5, the optimal tax is \$1.39/lb per grower per growing season. However, this value requires adjustment to \$8.03/lb and \$11.05/lb, respectively, to account for a 50% decrease in tomato price or a 50% increase in the production cost coefficient associated with the degradation rate. This observation is consistent with studies demonstrating that firms facing financial distress are more likely to violate environmental regulations or forgo investments in cleaner technologies (Xu and Kim 2022; Atkinson 2023; Oestreich and Tsiakas 2024). Therefore, social planners may need to implement stricter environmental policies, such as higher taxes, to align grower behavior with socially optimal outcomes.

[19]We also tried different restrictions and total number of growers, and we got the similar outcome. The limitation of 400 lb. for 130 growers is equal to 3.08 lb per grower.

Table 5. Optimal steady-state disposal method, under the corrective tax

	Disposal method	Degradation rate (δ_{it})	Plastic pollutant in the farm-land soil (lb.) (S_{it})	Optimal tax ($/lb) ($\tau_{i,t}$)	Plastic pollutant in the landfill from the farm (lb) ($h_t(.,z_t)$))
Social Planner Optimum (Baseline)	In soil	96%	3.08	1.39	0
Social Planner Optimum (Crop Price decreases 50%)	In soil	96%	3.08	8.03	0
Social Planner Optimum (The coefficient of Production cost associated with degradation rate increases 50%)	In soil	96%	3.08	11.50	0

Further research is needed to fully understand the interplay between corrective taxes and the financial challenges faced by growers.

Although we found that corrective taxes can incentivize BDMs adoption, potential unintended consequences such as farmer resistance (Carattini et al 2018), logistical challenges in implementation (Cai et al 2022) and the impact of limited factor mobility, corruption, and imperfect competition on the distribution effect of taxes (Fullerton and Muehlegger 2019) need to be considered. Exploring alternative policy instruments, such as subsidies for BDM adoption (Velandia et al 2020 c) or educational programs (Dentzman and Goldberger 2020), could enhance the effectiveness of promoting sustainable agricultural practices and mitigating plastic pollution in future research.

Stochastic environment

We extend the analysis of plastic mulch degradation by incorporating uncertainty into the model (see Appendix C). Recognizing that factors like weather and climate can significantly impact the degradation of plastic pollutants in farmland soil, a stochastic element is introduced to the model. This allows for the examination of how variability in degradation rates, potentially influenced by factors like temperature, rainfall, and soil conditions, affects growers' decisions regarding biodegradable mulch adoption.

The stochastic analysis reveals that while short-term weather fluctuations may not significantly impact the average degradation rate or long-term plastic accumulation, consistent slowdowns in degradation, potentially linked to climate change, incentivize growers to adopt faster-degrading biodegradable mulches. Farmers are more likely to embrace innovation when facing climate challenges (Rising and Devineni, 2020). Furthermore, Feder et al. (1985) provide a comprehensive overview of the uncertainties influencing technology adoption in agriculture. Our work builds upon their findings by demonstrating that increased variability in plastic pollutant stock can negatively affect expected grower profits and amplify profit uncertainty. This underscores the importance of considering uncertainty in degradation processes when making decisions about plastic mulch management and highlights the potential economic benefits of adopting biodegradable options, particularly in the context of a changing climate.

Grower risk aversion analysis

Since the use of BDMs introduces profit uncertainty due to weather and climate variability, it is important to understand if a grower's risk preference impacts the optimal choice of mulch adoption. Relaxing the assumption of a risk-neutral grower with a linear utility function of lifetime profit, we assume a constant absolute risk aversion exponential utility function (Pratt 1964; Phelps 2024) as shown in Equation 23, where r is the Arrow-Pratt coefficient of absolute risk aversion (Mas-Colell et al 1995).

$$U(\pi_i) = \frac{1 - e^{-r\pi_i}}{r} \tag{23}$$

Given the profit uncertainties associated with BDMs, the expected utility of using mulches is given by Equation 24. We assume that lifetime profit, π_i, follows a normal distribution with mean μ_π and standard deviation σ_π.

$$EU(\pi_i) = \frac{1 - e^{-r\mu_\pi + \frac{(r\sigma_\pi)^2}{2}}}{r} \tag{24}$$

To understand how grower risk preference influences mulch adoption, we examine the difference in expected utility between using BDMs with profit uncertainty and using PEMs with profit certainty. We use the stochastic baseline scenario in Table C1 (Appendix) to illustrate our findings. Under the risk-neutral assumption, the landfill cost is high enough that growers choose BDMs, earning a profit of \$136,740.37, which is \$800 more than using PEMs[20]. However, the standard deviation of BDM profit is \$25.30.

We consider three scenarios for the grower's constant absolute risk aversion utility function: risk-neutral ($r = 0.001$), moderate risk aversion ($r = 0.01$), and high-risk aversion ($r = 0.1$). Figure 3 shows that as the grower becomes more risk-averse, the difference in expected utility between using BDMs and PEMs decreases. When the grower is risk-neutral (Point A in Figure 3) or moderately risk-averse (Point B in Figure 3), they gain more utility from using BDMs. However, when the grower is highly risk-averse (Point C in Figure 3), they do not gain more utility by switching from PEMs to BDMs.

Our findings reveal that while risk-neutral and moderately risk-averse growers are more likely to adopt BDMs due to the increased expected utility of profit, high-risk-averse growers tend to avert BDM adoption despite the financial benefits. This highlights the importance of considering grower risk preferences when designing policies and incentives aimed at promoting BDM adoption.

Furthermore, this analysis complements and extends our previous findings on the impact of economic incentives, such as landfill fees and corrective taxes, on BDM adoption. While economic incentives can play a significant role in encouraging BDM adoption, the effectiveness of these incentives may be constrained by grower risk aversion. Therefore, a comprehensive approach that considers both economic and behavioral factors is crucial for promoting the widespread adoption of BDMs.

Conclusions and possible extensions

This research contributes to the existing literature by developing a dynamic economic model to analyze the complex problem facing farmers and policymakers' trade-off between the environmental benefit of BDMs and their performance in agricultural production. The numerical solutions of the illustrative case study, generated under both deterministic and

[20]The profit from using PEMs is \$135,940, while the landfill tipping fee is \$0.105 per pound.

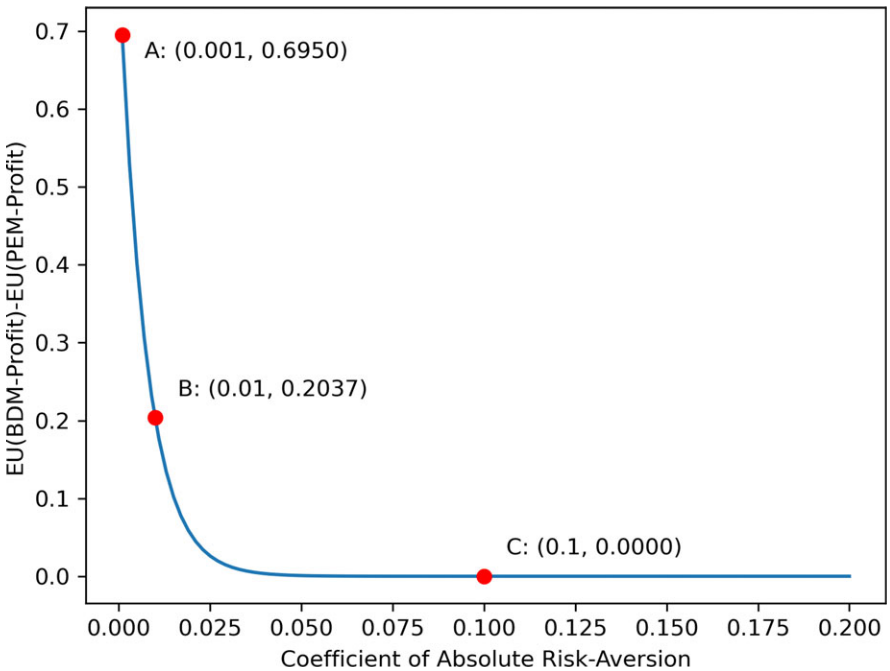

Figure 3. Difference in expected utility between using BDMs and PEMs under different coefficients of absolute risk aversion.

stochastic scenarios, offer valuable insights into the impact of economic incentives and policy interventions on plastic mulch choices and pollution levels.

The theoretical analysis reveals that growers prioritize long-term soil improvement and higher yields when crop prices are high, opting for faster-degrading mulches even with higher upfront costs. Similarly, higher disposal costs incentivize the adoption of faster-degrading mulches to minimize disposal volume and associated costs. Essentially, growers weigh the benefits of faster degradation (reduced disposal costs and improved soil health) against the potentially higher upfront cost of BDMs. This finding aligns with existing research on farmers' interest in maintaining or increasing soil quality, where crop prices positively influence investments in soil conservation (Issanchou et al. 2019).

Empirical analysis of tomato production in Washington State supports these theoretical findings. While growers currently favor conventional plastic mulches (PEMs) and landfill disposal due to lower costs, increasing landfill tipping fees and crop prices could drive the adoption of BDMs. However, the study also reveals that current biodegradation standards might not incentivize the use of BDMs with the fastest degradation rates due to limited economic benefits. This challenge is not unique to BDMs, as other certification programs, such as organic and Fair-Trade coffee certifications, face similar issues (Seufert et al. 2012; Dragusanu et al. 2014).

A corrective tax on plastic waste is identified as a potential policy tool to encourage environmentally optimal behavior by promoting BDM adoption and reducing landfill disposal. However, when growers face financial distress, i.e., crop price decreases or production cost associate with mulch degradation rate increases, higher corrective taxes may be necessary to align their behavior with socially optimal outcomes. To prevent non-compliance by private decision makers during financial distress (Xu and Kim 2022; Atkinson 2023; Oestreich and Tsiakas 2024), a higher corrective tax may be necessary.

Finally, the study highlights the importance of considering uncertainty in degradation processes, particularly in the context of a changing climate, which can influence grower decision-making and the long-term accumulation of plastic pollutants in the environment. Furthermore, the analysis of grower risk aversion reveals that high-risk aversion can hinder BDM adoption, suggesting the need for policies that address both economic and behavioral factors.

Our findings have significant practical implications for both growers and policymakers. First, the model provides a framework for growers to evaluate the economic and environmental trade-offs of different plastic mulch choices, helping them make informed decisions that balance profitability and sustainability. Second, the study highlights the potential of economic incentives, such as landfill tipping fees and corrective taxes, to drive the adoption of BDMs and reduce plastic pollution. This information can be used by policymakers to design effective policies that promote sustainable agricultural practices.

Future research could explore several areas to further enhance our understanding of BDM adoption and plastic pollution control. First, it would be valuable to investigate farmer adoption behavior under real-world conditions, considering factors such as, information access, behavioral economics (e.g., nudging), and social norms. Second, field trials could be conducted to validate the model's assumptions and assess the long-term impact of BDMs on soil health and crop yields. Finally, the model could be extended to analyze the potential of other policy instruments (Baumol et al 1988), such as subsidies (Velandia et al 2020 c) or extended producer responsibility schemes, to promote BDM adoption and reduce plastic pollution.

While our model is designed for the agricultural sector, its framework can be extended to analyze single-use plastic problems in the retail sector. However, this extension requires several key assumptions. First, consumers must derive utility from consuming disposable plastic products (Jiang 2016). Second, their utility must decrease as plastic pollution increases. Applying the model to the retail sector requires a more detailed understanding of consumer decision-making. Nevertheless, the framework presented here serves as a strong foundation for future research. Additionally, our current work focuses on a production function approach, examining the impact of plastic residue on soil yield and revenue. A future avenue of research could explore a dual cost function approach, particularly relevant when the cost of removing plastic residue becomes infinitely high as levels increase (or conversely, as plastic residue approaches zero).

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/age.2025.20

Data availability statement. The authors confirm that the data supporting the findings of this study are available within the article. The simulation code that support the findings of this study are available from https://github.com/YoYo-JDCE/BDMs-Jiang-Marsh-Belasco.git .

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