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Risk and uncertainty of plastic mulch adoption in raspberry production systems

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Abstract

Agriculture plays a central role in providing food security and essential goods globally. Producers must consider and manage risk to ensure that the production system and its associated individuals are capable of enduring unexpected and disruptive events. Analyzing the different types of risk and accompanying uncertainties that growers experience can be essential to better reflect and understand the realities of their circumstances, but these concepts are not always accounted for in the adoption process. Drawing on the importance of risk and uncertainty, this study aims to assess the different types of risk and uncertainties involved in the risk decision-making process of the processed raspberry industry, where plastic mulch is a new production technique. Semi-structured interviews were conducted with participants involved in the use, research, outreach, manufacturing, and distribution of plastic mulch, specifically polyethylene (PE) mulch and soil-biodegradable mulch (BDM). Findings indicate that risk can be present in various forms including production, price, and hidden risks, with production and price risks being the most significant to all participants. When accounting for overall risk, PE mulch was considered riskier to industry representatives but less risky to growers and most research and outreach specialists. BDM was considered risky due to the uncertainties about durability, degradability, and the unknown impacts on the environment if BDM fragments do not degrade readily. The application of PE mulch and/or BDM can be beneficial for the raspberry production systems but will require time for additional research and effort to disseminate information to a wider agricultural audience.

Introduction

Risk has long been considered a limiting factor to technology adoption in agricultural production systems; however, the role of risk in the innovation-decision process is not always thoroughly investigated (Marra *et al.*, 2003; Komarek *et al.*, 2020). Risk is present in all aspects of agriculture because every decision that is made will inevitably have an impact on the future of the production system (Hardaker, 2004; Crane *et al.*, 2013). Therefore, producers must consider and manage risk effectively to ensure that the production system and its associated stakeholders are capable of enduring unexpected and disruptive outcomes (Hardaker, 2004). Farming in general is a risky occupation and most of the decisions that growers make regarding field work and management are dependent on ever-changing biotic and abiotic factors. As a result, risk and uncertainty behaviors among growers have historically involved incorporating risk-reducing strategies that provide them with flexibility, diversification, and profit (Hamsa and Bellundagi, 2017).

The concepts of 'risk' and 'uncertainty' are related but differ from one another in a decision-making framework (Huirne, 2003). 'Risk' is applied to situations where there exists a distribution of known outcomes and the probabilities of the potential outcomes are known, whereas 'uncertainty' is applied to situations where the outcomes and the probabilities of the potential outcomes are unknown (Knight, 1921; Komarek *et al.*, 2020). Uncertainty also encompasses unanticipated events that were not perceived as possibilities (Just, 2001). Additionally, uncertainty exists in situations where there is insufficient information available, which may limit an individual's ability to consider every possible outcome at the moment of making a decision (Just, 2001; Huirne, 2003).

Risk and uncertainty are especially important to understand as there is significant interest among government and research institutions to promote the adoption of new technologies that have the potential to create more productive and/or sustainable production systems (Pannell, 2003). However, studies have demonstrated that regardless of the potential benefits that can be acquired by using newer technologies, growers usually adopt them at slower rates than institutions desire (Grabowski *et al.*, 2016; Ruzzante *et al.*, 2021; Makinde *et al.*, 2022). Risk may inherently involve exposure to unwanted, negative consequences such as reduced crop yields and profit, but can also be rewarding to a grower, for example if the end-of-season profits are higher than anticipated (Huirne, 2003; Komarek *et al.*, 2020). A current and prime example of this is the promotion of plastic mulch in floricane raspberry (*Rubus idaeus*) production systems. Plastic mulch is used widely to grow specialty crops such as strawberry (*Fragaria × ananassa*) and various vegetables. They are relatively inexpensive, easily accessible and are favored by many growers because they can help improve crop yields and quality (Kasirajan and Ngouajio, 2012). However, raspberries are traditionally grown without plastic mulch due to their perennial growth habit and shoots (primocanes) that emerge from the soil each year, but this is changing. In recent years there has been an increase in adoption of both nondegradable, polyethylene (PE) mulch and soil-biodegradable mulch (BDM) by raspberry growers in our study site: western Washington State.

Washington State leads in production of processed raspberry in the United States, representing 52 and 33% of total raspberry acreage and fruit production, respectively (Kramer *et al.*, 2021). The processed raspberry industry in Washington is also highly concentrated with 99% of in-state production coming from a single county (United States International Trade Commission, 2021). It is important to understand the risk management considerations that are influencing the use of plastic mulch among Washington raspberry growers. In this paper, the concept of risk is used to assess the different risk types that are involved in the use of PE mulch and BDM based on the experiences of growers who historically have not relied on the use of plastic mulch in their production systems. We also consider the perspectives of research and outreach specialists and industry representatives (e.g., mulch manufacturers and distributors). In addition, this study aimed to gain a deeper understanding of the uncertainties that all participating groups may have about using PE mulch and/or BDM. Gaining an in-depth social science understanding of the key factors involved in the risk decision-making process of plastic mulch utilization in raspberry systems can provide information that may direct new research, support educational material development, and/or influence changes in policies that can help meet the needs of growers (Mills *et al.*, 2011; Breukers *et al.*, 2012; Beissinger *et al.*, 2018).

Conceptual framework

Risk and uncertainty in agriculture

When a new technology is introduced to a group of growers there is generally some hesitation about it. During the initial stage of technology adoption most of the agriculture community is conservative and rejects the technology (Cancian, 1980). Access to information is a key element to adoption (Ruzzante *et al.*, 2021), with positive information about the potential benefits of a new technology leading to faster diffusion (Foster and Rosenzweig, 2010). Grower communities are generally composed of different types of adopters, including innovators, early adopters, and later adopters (Rogers, 2003; Ruzzante *et al.*, 2021). Growers who initially reject a technology often observe and learn from the experiences of the early adopters. Their observations therefore have an impact on their perceptions, which influences future decisions to adopt. Technology adoption may also be influenced by grower education, farm size, land tenure, and access to credit and extension services (Ruzzante *et al.*, 2021). Risk due to limited capital or access to credit have been reported to be especially important in delaying or preventing growers from incorporating new technologies into their production systems (Foster and Rosenzweig, 2010). However, it is important to note that growers in all scenarios are exposed to risk to a varying extent, although uncertainty tends to be lower for later adopters (Cancian, 1980).

Risk and uncertainty have been around since the earliest days of agriculture. However, researchers have expressed concerns that agricultural risk studies have not been effective in emphasizing the importance of risk-averse behavior (Just, 2003; Komarek *et al.*, 2020). In addition, many researchers have asserted that previous literature has primarily focused on less complicated risk types, such as production risk related to weather changes, and in general does not consider multiple sources of risks simultaneously (Chambers and Quiggin, 2004; Komarek *et al.*, 2020). Komarek *et al.* (2020) reviewed 5294 studies published between 1974 and 2019 and concluded there are five major types of agricultural risk (production, price, financial, human, institutional) but only 66% of studies evaluated one or more risk type and only 15% of studies considered all five risk types. Analyzing the different types of risk that growers experience can provide a broader interpretation of the factors that influence their decisions and help us better reflect and understand the realities of their circumstances. Researchers and institutions should consider these types of risk to help gain an in-depth understanding of the information needed to help growers adapt and manage risks in the everchanging nature of the agriculture sector.

Risk types and sources of risk

Every business operation must manage risks in one way or another; however, agricultural production systems are specifically exposed to risk because of the various and unpredictable changes that can occur with abiotic and biotic factors, which create uncertainty about how crops will perform each season (Hamsa and Bellundagi, 2017). Risk can be present in various forms and it is common for different types of risks to co-occur or reinforce one another (Intergovernmental Panel Climate Change, 2019; Komarek *et al.*, 2020). In most studies researchers have categorized risks into five major risk types: production, price, financial, human, and institutional risks (Komarek *et al.*, 2020). However, some literature (Carolan, 2006; Bairwa *et al.*, 2013) indicates that growers may face two additional risk types: hidden and asset risk. Therefore, seven risk types are described below.

1) *Production risk*: Agricultural production is a product of biology and environmental interactions within an agroecosystem. Decision-making at the farm level thus depends on uncontrollable and unpredictable conditions. This can include meteorological events, such as extremes in temperature and rainfall, as well as pests and diseases (Bairwa *et al.*, 2013; Hamsa and Bellundagi, 2017). Products from these events can cause uncertainty about how crops or livestock may perform in the future (Hardaker, 2004). Additional environmental factors that can reduce or limit crop yields also fall under this category (Komarek *et al.*, 2020).
2) *Price risk:* Price risk refers to unforeseen fluctuations in the price of a crop or livestock output and/or the cost of farm inputs that are purchased after a grower decides to commit to production (Bairwa *et al.*, 2013). Access to markets is also included in this risk type (Komarek *et al.*, 2020). Production generally requires time and ongoing investments of farm inputs (e.g., fertilizer, pesticides, feed, and/or equipment) to produce a quality crop and high yields. In most cases growers do not produce a profit from these investments for several

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months or years. Growers are not guaranteed the same product prices that were established before committing to production (Bairwa *et al.*, 2013). By the time the crop is ready to be distributed to consumers there is a possibility that market prices could decline, reducing the overall profitability of the production system. The price of crops is also dependent on domestic and international markets, which are complex and can change abruptly. Additional sources of price risk include market access, which is influenced by international trade, protectionism, and liberalization as well as unequal access to information (Komarek *et al.*, 2020).

3) *Financial risk*: Financial risk is related to the economic viability of a production system but differs from price or market risks. It can also be defined as the variability of a production system's cash flow (Gabriel and Baker, 1980; De Mey *et al.*, 2016; Komarek *et al.*, 2020). This type of risk is dependent on how the grower chooses to obtain or finance capital for crop or livestock production investments (Bairwa *et al.*, 2013). A grower who makes the decision to borrow capital may experience variation in interest rates on loans, changes in credit conditions, or face legal repercussions if the production system generates insufficient capital to repay creditors (Bairwa *et al.*, 2013).
4) *Human risk*: Human risks are associated with the individuals involved in a production system, including the operator(s) or farm household (Hardaker 2004; Komarek *et al.*, 2020), and derive from well-being or personal relationship issues. Sources of human risk can have a negative impact on the future profitability of the production system such as personal injury from operating farm equipment, illness or death caused by natural diseases as well as diminished health from exposure to agrochemicals, or any other disruptive change to the health of the stakeholder(s) (Antle and Pingali, 1994; Lopes Soares and Firpo de Souza Porto, 2009; Arana *et al.*, 2010; Bairwa *et al.*, 2013).
5) *Institutional risk*: Agricultural production systems are also affected by unpredictable changes in policies and regulations by either informal or formal institutions. Sources of informal institutions include rural producer organizations as well as changes in social norms while the government is identified as a formal institution (Hardwood *et al.*, 1999; Komarek *et al.*, 2020). Modifications made by these institutions can establish constraints for a production system that may affect the price of essential production inputs or output prices (Bairwa *et al.*, 2013). Changes in pesticide regulations, for example, can impact a grower's investment costs. Policy and regulation modifications may also influence a change in crop price if a foreign country decides to stop or limit product imports due to abrupt institutional changes.
6) *Hidden risk*: Hidden risks do not have direct and visible consequences (Carolan, 2006). For example, if a grower decides to till their field, they cannot directly see the impact of tillage on soil structure and health, soil microorganism diversity or community size, nor the soil's ability to hold water and/or nutrients. The grower may be able to indirectly observe the consequences in the future based on the crop's growth and development, but these types of risks are not always detectable at first glance.
7) *Asset risk:* All business owners including growers may be subject to the loss or damage of assets including crops, livestock, equipment, or infrastructure due to theft, fire, or other unpredictable events. This risk is assumed for all types of farming operations (Bairwa *et al.*, 2013).

Agricultural plastic mulch

Agricultural plastic mulch has been utilized in various specialty cropping systems for decades and are favored by many growers due to the horticultural benefits they can provide such as helping moderate soil temperatures, reducing water use, suppressing weed growth, and enhancing crop yield and quality (Kasirajan and Ngouajio, 2012). The effects of plastic mulch have been thoroughly studied using various annual vegetable and fruit crops, but studies involving perennial production systems are limited (Zhang *et al.*, 2021). Evidence of the potential benefits of plastic mulch in addition to it being relatively affordable, easily accessible, and durable have influenced a steady adoption across production systems globally. This trend is expected to continue rising and by 2025 the global market for plastic mulch is estimated to expand at a compound annual growth rate of 6%, achieving a market value of $15 billion USD (Industry Analysis Research Consulting, 2019). Despite the benefits, there are tradeoffs associated with the use of plastic mulch that have indicated it to be unsustainable (Steinmetz *et al.*, 2016; Shah and Wu, 2020). The most common types of agricultural plastic mulch used are manufactured using low-density polyethylene and linear low-density polyethylene (Sintim and Flury, 2017). These plastic polymers are derived from non-renewable, petroleum-based feedstocks that are not biodegradable (Shah and Wu, 2020), thus PE mulch should be removed and disposed at the end of the cropping cycle. However, used PE mulch is usually contaminated with adhered soil, plant debris, and agrochemicals thereby limiting the number of recycling facilities that are willing and able to recycle it (Moore and Wszelaki, 2016). As a result, most growers resort to alternative disposal pathways that include landfilling, open-burning, on-site burial, and stockpiling (Goldberger *et al.*, 2019). Landfilling can be laborious and expensive for growers (Velandia *et al.*, 2020), and open burning is illegal in various states (Corbin *et al.*, 2013). On-site burial and stockpiling can also have undesirable effects as the formation of micro- and nanoplastics over time can carry adsorbed agrochemicals throughout soils and into adjacent waterways (Kasirajan and Ngouajio, 2012). Thus, poor management of used PE mulch has generated multiple economic, environmental, and waste management concerns (Singh and Sharma, 2008).

To mitigate concerns with PE mulch, there has been increased interest in BDM among growers, research and outreach specialists, and industry representatives. Commercial BDM is currently composed of a blend of bio- and fossil-fuel based feedstocks (DeVetter *et al.*, 2021), and are designed to be tilled into soil where microorganisms can degrade and convert the plastic mulch into microbial cell biomass, carbon dioxide, and water under aerobic conditions (Kasirajan and Ngouajio, 2012; Hayes *et al.*, 2019). BDM is similar in appearance to PE mulch and can provide comparable benefits (DeVetter *et al.*, 2017; Ghimire *et al.*, 2018, 2020; Zhang *et al.*, 2020*a*). Replacement of PE mulch with BDM has the potential to reduce the quantity of plastic waste generated and can help offset some of the negative consequences associated with the lack of sustainable disposal pathways of PE mulch. However, the application and use of BDM in specialty cropping systems is not a new practice. BDM was introduced during the 1980s, but adoption was low due to its varying and unpredictable rates of degradation in soil (Sintim and Flury, 2017). Competition with oxo-degradable and photo-degradable plastic mulch in the 1980s and their mislabeling as biodegradable also affected BDM adoption (Kasirajan and Ngouajio, 2012). Under field conditions, oxo- and photo-degradable plastic mulch deteriorates when exposed to UV light, heat and/or oxygen. However, the fragments and micro- and nanoparticles produced are not degradable. The plastic residue therefore becomes a source of pollution as it accumulates in the soil and nearby waterways over time (Miles, 2017). In addition, the premature and unpredictable breakdown of oxo-degradable mulch contributed to increased cost for weed control and end-of-season removal activities, which negatively impacted the perception of BDM. Commercially available BDM today has been reformulated and are more promising than the products utilized in previous years. BDM research is ongoing and focused on evaluating the functionality and degradability of different BDM formulations under diverse field and soil conditions. Multiple studies (e.g., Sintim *et al.*, 2020; Griffin-LaHue *et al.*, 2022) have demonstrated more consistent rates of BDM degradation in soil, nonetheless most of the agricultural community is still hesitant to use them (Madrid *et al.*, 2022). Given that PE mulch and BDM are associated with different types of risk, it is important and worthwhile to investigate what factors should be considered when making the decision to utilize either type of plastic mulch.

Case of Western Washington raspberry production

As national leaders of processed raspberry production, Washington growers accounted for approximately \$530 million of the approximately \$1 billion U.S. processed raspberry market between 2015 and 2020 (USITC, 2021). At the same time, it was reported that about \$740 million of the total U.S. market sales came from processed raspberry imports. Consumer demand for raspberries in the U.S. was relatively stable between 2015 and 2019. However, increasing competition between the U.S. processed raspberry industry and international raspberry importers from Mexico, Chile, Serbia, and Canada have caused a decline in U.S. prices (USITC, 2021). Given the market landscape, growers must be careful and purposeful with their decisions to be able to adapt and limit undesirable consequences that could negatively impact their livelihood and the future profitability of their production system.

Floricane raspberry in Washington is traditionally grown in bare (nonmulched) raised beds using plant root cuttings or bare root canes. Advances in technology and research have improved tissue culture (TC) techniques that allow nurseries to quickly propagate large quantities of plants that are normally free from disease and viruses (DeVetter *et al.*, 2022), which is appealing to many growers. Some limitations of TC raspberry plants are that they are small, fragile, and have a lower likelihood of survival if planted directly into a field. The TC plants are also susceptible to herbicide injury thereby limiting the use of herbicides during establishment. Hand weeding can be used as an alternative management strategy, but it can be costly and require many hours of manual labor. The TC plants are also generally more expensive than traditionally grown nursery stock, thus any strategy that can be used to protect and support their establishment in-field can be valuable for growers. Research conducted in recent years has shown that plastic mulch has the potential to enhance TC establishment and productivity in raspberry production systems (Zhang *et al.*, 2019, 2020a; DeVetter *et al.*, 2022). However, the use of 'plasticulture', otherwise known as the inclusion of plastic in production systems in the form of but not limited to plastic mulch such as PE mulch and BDM (Kasirajan and Ngouajio, 2012), is a relatively new management approach for commercial production systems and its long-term effects are not currently well known. Gaining a better understanding of the factors influencing adoption with an emphasis on risk and uncertainty will enable a more holistic understanding of the potential utility of plastic mulch in raspberry operations and will inform outreach approaches.

Methods

Participants were recruited with the help of Washington State University Extension educators and as recommended by the participants themselves (i.e., snowball sampling). Requirements for participation included (1) having experience within the processed raspberry industry as the owner of the production system, operations manager, or researcher; (2) having experience with research and/or outreach related to PE mulch and/or BDM in western Washington; or (3) being involved in the extrusion, manufacturing, and/or distribution of PE mulch and/or BDM to growers in the region. A total of 27 individuals participated in the study: 7 growers that represented approximately 39% of Washington's raspberry acreage, 9 leading research and outreach specialists, and 11 industry representatives that serve as primary mulch suppliers in North America.

An interview guide (available as a Supplementary file) was prepared prior to the interviews and included prompts to acquire information about where the participants had learned about PE mulch and/or BDM, what factors and crop production considerations influenced the decision to use either product, and general perceptions and concerns about PE mulch and BDM. In addition, the study participants were asked if they had questions about using PE mulch and/or BDM and what research was needed to help reduce the knowledge gap about plastic mulch use in raspberry production systems.

All interviews were audio-recorded with the approval of the participants. Interviews were then transcribed by one of the authors. Data analysis involved generating codes or 'thematic tags' (Orne and Bell, 2015) using a combination of deductive and inductive coding. Deductive coding relies on existing theory to construct response categories, while inductive coding is more exploratory (Frankfort-Nachmias and Nachmias, 2008). Portions of the participants' statements were coded as either 'risk' or 'uncertainty'. Following inductive coding, risks were then categorized into one (or more) of the seven risk types highlighted previously: production, price, financial, human, institutional, hidden, and asset. An additional risk type (esthetics) emerged through deductive coding. The relative importance of perceived risks was then assessed by examining the frequency a risk type was mentioned by the study participants. Table 1 lists the risk types mentioned most frequently by the three groups of study participants.

Results

Analysis of the interview data focused on the differences in risk/uncertainty statements among the three groups of study participants (growers, research and outreach specialists, and industry representatives) and in experiences with the two types of plastic mulch (PE mulch and BDM). Most research and outreach specialists as well as industry representatives had experience with both types of plastic mulch, but few growers had experience with BDM. There was some variation between the risk types mentioned by the different groups as well as additional barriers that could impact adoption (Table 1), which are discussed below in further detail under the corresponding risk type.

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Table 1. Summary of the risks discussed by participating groups (growers, research and outreach specialists, and industry representatives), arranged by risk type from highest to lowest significance

	Growers		Research and outreach specialists		Industry representatives	
Risk types	PE[a]	BDM[b]	PE	BDM	PE	BDM
Production						
Stress on roots	✓		✓			
Reduction of primocane establishment	✓	✓	✓	✓	✓	
Increase of soil-borne pathogens	✓		✓	✓		
Price						
High mulch cost		✓		✓		✓
Increased labor cost			✓		✓	
High disposal fees			✓		✓	
Hidden						
Reduced soil health			✓	✓	✓	
Micro-plastic translocation into nearby ecosystems	✓	✓	✓	✓	✓	
Esthetics						
Untidy appearance of farm		✓		✓		

[a]Polyethylene mulch.
[b]Soil-biodegradable mulch.

Production risk

The primary type of risk discussed by the participants was production risk. Plastic mulch can support newly planted TC plants but there is a possibility that utilizing PE mulch and BDM can impact the health and development of raspberry over time. Most studies have focused on the impact of plastic mulch on annual crops, but raspberry is a perennial crop and researchers have cautioned that plastic mulch may aggravate soilborne disease and plant parasitic nematode problems due to changes in soil temperature and moisture (DeVetter *et al.*, 2022). When asked about the specific factors that influenced their decision to incorporate PE mulch or BDM into their raspberry production system, some of the growers specified:

'I needed help with weed control and moisture control. Those were probably the two biggest things in establishing these tender little plants. And then we had the third real positive: [Mulch] greatly enhanced growth. Consistent growth. That's kind of the gravy on the whole thing.' (Grower 2)

'It started out with the issue with weed control and baby plantings with live [TC] plug plants. At that point, some people had done a couple different things with preemergence [herbicides] and things like that, but everybody was a little bit nervous about that, especially when raising plants being worth what they are and everything else.' (Grower 6)

Many research and outreach specialists also mentioned that incorporating plastic mulch into a raspberry production system can support better establishment of TC plants. One in particular stated:

'I mean you're looking at the plastic mulch potential of having two benefits. One is better planting establishment because of the higher temperature and TC plants. The other potential benefit is obviously for weed management, reducing weed management costs.' (Research Specialist 9)

PE mulch

In the case of PE mulch all growers brought up concerns about the potential risk related to production or yield. PE mulch may create favorable conditions in soils that support the development of insects and soil-borne pathogens. Multiple growers mentioned:

'What impact would it have on insects? What impact would it have on diseases? Could we increase the risk? You know, for instance, with being in a more humid environment?' (Grower 4)

'I'm a little bit worried about creating an environment under that plastic that is potentially open to some sort of soil disease that might not be present otherwise because you're creating this kind of impact. [A] warm, moist environment down there that in my thinking would be pretty hospitable to a couple different things.' (Grower 6)

Additional production risks of using PE mulch in raspberry production systems include the risk of negatively impacting root development, and establishment of primocanes (vegetative shoots that bear fruit after overwintering), which could impose greater stress on raspberry plants and affect yields. Nearly all the growers expressed this concern, and one individual declared:

> 'Primocane growth was the biggest [concern] for me, because … the choking in the enclosed bed may not allow primocanes to grow. Other than that, it was uncertainty on what was going to come of it.' (Grower 4)

Some growers observed negative yield impacts on their crops in the second year, which may be related to the application and impacts of PE mulch during the first year:

> 'The second-year cane numbers seem to be decreased everywhere. We've done it. Raspberry yields have held up [the first year]. We've had trouble the second [year]. Is it maybe that we are getting a tremendous crop the first year? … So, are we growing so big that we're crowding out new shoots because of the plastic [mulch]?' (Grower 3)

Most research and outreach specialists reflected on the same three sources of production risks, with one research and outreach specialist elaborating on the potential negative effect on crop health:

> 'Some growers have been very hesitant [of using PE mulch] because of [the need to drip irrigate and fertilize underneath], in addition to the impact of what the high soil temperature may have on root growth because raspberry is a very temperate crop, and the negative impact it could have on primocane numbers per row.' (Research and Outreach Specialist 9)

Research and Outreach Specialist 9 was asked to elaborate on the potential impact that plastic mulch could have on raspberry plants due to increased soil temperatures and she clarified that this has not been studied under field conditions, but with raspberries grown in containers the high soil temperatures have reduced the performance of the crop:

> 'We see a reduction in root growth in terms of what we can see, and it could go deeper in soil. We see shorter cane growth, fewer cane number, shorter internodes, and in primocane fruiting cultivars, we see stress, leading to early flowering which ends up being lower in yield.' (Research and Outreach Specialist 9)

Few industry representatives elaborated on the potential drawbacks of growing raspberries using PE mulch. The participants mentioned that it is possible for PE mulch to pose a production risk to raspberry growers if the plastic mulch limits primocane growth, reducing crop establishment in subsequent years. Differences between industry representatives and the other participating groups were likely related to knowledge gaps in production. The crop production benefits of PE mulch in cropping systems are widely known (Kasirajan and Ngouajio, 2012), and industry representatives are knowledgeable of the application of PE mulch within annual systems. However, raspberry production using PE mulch is a relatively new management approach and many of the industry representatives had minimal to no experience in perennial systems including commercial raspberry systems.

BDM

Sources of production risk were also associated with BDM, but to a lesser extent than PE mulch. A grower with experience using BDM did not express great concern about potential negative impacts on production or yield, although he did mention reduction of primocane establishment could be a factor to consider in other raspberry systems. The grower in this case only used BDM short-term to support TC plant establishment. By the time the TC plants reached maturity the BDM was no longer in place and functional.

The same source of risk, in addition to a potential increase of pest and soil-borne diseases, were mentioned by most research and outreach specialists. The reasoning was the same as that for PE mulch use. In contrast, industry representatives did not find BDM to pose risks to production or yield. This difference in perspective could also be related to knowledge gaps about raspberry plant growth and development in production systems using BDM. More information is necessary regarding interactions among production practices (e.g., irrigation and fertilizer rates, pruning, pest management, timing of mulch removal) and BDM to gain a better understanding of potential sources of production risk.

Price risk

Price risk was the second most common risk type mentioned by all participating groups. When looking to utilize plastic mulch regardless of the product type, there were multiple factors considered before deciding to make the capital investment. As one research and outreach specialist stated:

> '[Because plastic mulches are not traditionally used in raspberry production systems] there's a certain amount of reservation on the part of growers to try something new and different because there's a lot of costs involved.' (Research and Outreach Specialist 1)

PE mulch

The decision to incorporate PE mulch into a raspberry production system involved not only a higher upfront cost for the plastic mulch product, but also the cost for the mulching equipment, labor to apply the plastic mulch on raised beds, labor to remove the plastic mulch mechanically or manually at the end of the growing season, and the expense to transport and dispose the plastic mulch at a nearby landfill or recycling facility (Madrid *et al*., 2022). Growers who adopted PE mulch and planned to continue using it acknowledged that there is a higher price associated with using PE mulch compared to growing raspberry in a non-mulched system, but they were willing to pay the costs because of positive effects (e.g., weed suppression) they observed in their fields, which translated to better establishment of TC plants, reduction of pesticide use, water conservation, healthier vegetative growth, and improved yield outcomes. Growers also acknowledged that these horticultural benefits come with a high price because of removal and disposal, yet the six growers were not too concerned because the horticultural benefits were considered worth it. Thus, growers accounted for the labor and disposal costs upfront, before making the decision to use PE mulch. In this case growers had some awareness of the investment costs. Deciding to incorporate PE mulch in their raspberry systems was not associated with price risk, however, these costs are considered barriers to adoption by growers who may not have the capital nor resources to change their production practices.

Research and outreach specialists and industry representatives also mentioned that higher costs could affect adoption, but they placed more emphasis on removal and disposal costs, which were brought up as potential influencing factors to replace PE mulch with BDM. PE mulch must be removed and disposed at the end of each season. Labor availability can vary, which may affect the cost of labor and pose a price risk to growers. In addition, most growers dispose of used PE mulch at landfills and tipping fees differ by region (Madrid *et al*., 2022). A decrease in available land and increase in concern about the release of hazardous byproducts by landfills (Steinmetz *et al*., 2016) may change the cost of disposal in the future. For growers this adds a second price risk to consider when making the decision to use PE mulch.

Differences in perception of price risk among the participants could be related to the objectives of each participant's profession. The potential long-term effects of PE mulch use are factors currently driving the work of research and outreach specialists. Industry representatives, in contrast, are focused on finding an alternative to PE mulch. The goals of research and outreach specialists and industry representatives are different, but both aim to support the use of more sustainable plastic mulch options. Growers are aware of the drawbacks of using PE mulch; however,

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there are numerous factors (i.e., weather, pest, disease) they have to manage, many of which are unpredictable and out of their control. They may still consider end-of-life management of plastic mulch and future impacts of PE mulch on soil, but their main focus may be on factors that ensure a successful production season.

BDM

For BDM all participating groups mentioned that the purchase price of BDM was a primary source of price risk. A significant difference between PE mulch and BDM that was mentioned was that BDM has a higher purchase price than PE mulch. One grower with BDM experience argued that BDM is still worth using because it was able to provide similar crop production benefits as PE mulch. However, growers should consider how long they plan to use BDM to ensure it will last throughout the growing season. As grower 2 stated:

> 'Well, for the use of it [BDM], certainly we saw the benefit … [weed suppression, TC plant establishment], which is, I think pretty well understood in our industry of that additional growth response [crop growth]. Other than that, I'm only looking at a 3-month period of service for the way I use it. It could be very different in other cropping systems.' (Grower 2)

The service life of a BDM can vary by location, management practices, and weather variability (Li *et al.*, 2014; Sintim *et al.*, 2020; Zhang *et al.*, 2020*a*, 2020*b*). There is a risk that a BDM's durability may not align with a grower's intended production goals. Thus, the higher purchase cost of BDM may provide some level of price risk to growers, with growers having limited access to capital taking a greater risk.

Research and outreach specialists as well as industry representatives considered BDM purchase cost to be a potential barrier to adoption, although they did not perceive it as a price risk. Studies have shown that the cost of BDM has reduced the economic attractiveness to many growers (Mari *et al.*, 2019), and has led to the assumption that PE mulch is more economical to use than BDM. Velandia *et al.* (2020) reviewed the economics of using BDM and highlighted that BDM helps reduce end-of-season activities related with PE mulch removal and disposal, thus growers save on labor and can recover the higher market price of BDM. Galinato *et al.* (2020) also assessed the economic feasibility of using BDM but applied it to a pumpkin (*Cucurbita pepo*) production system to develop a baseline of input costs and returns. Findings from both studies demonstrate that replacing BDM with PE mulch can be cost effective. There may be minor discrepancies with the economics of BDM in a pumpkin production system compared to a raspberry system, and it is possible for some growers to perceive this information as unreliable for their production systems. Nonetheless, for a grower to truly know if BDM is the right economic decision for their production system, they must know the costs of the BDM, tillage, and PE mulch removal and disposal to develop a more precise assessment for their production system (Galinato *et al.*, 2020; Velandia *et al.*, 2020). As one research and outreach specialist claimed:

> 'You know if you can clearly show the cost benefit from an economic standpoint and clarify the impact on things like weed management and plant establishment, I think that should be sufficient.' (Research and Outreach Specialist 2)

Hidden risk

PE mulch

Multiple hidden risks were discussed by many industry representatives and research and outreach specialists, but only by a few growers. Sources of hidden risks associated with PE mulch were related to mulch composition because PE mulch is not engineered to biodegrade in soil and has the ability to persist in the environment for hundreds of years (Ohtake *et al.*, 1998; Hakkarainen and Albertsson, 2004). PE mulch is removed from the field after the cropping season; however, PE mulch residues remain in soil, which can lead to decreased soil health and function (Lozano *et al.*, 2021; Zhang *et al.*, 2020*b*). There is also risk that microbial activity may be negatively affected, threatening food production in the future. One research and outreach specialists mentioned:

> 'Polyethylene material does need to be properly removed because it's been shown it's not biodegradable and the plastic material will persist in soil for hundreds of years in different forms in big pieces, in smaller pieces, in micro-plastics. So, for sure, this is something we don't want to build up in soil. [It] has been shown by studies, especially in China, that in some crops the reduction of yield has been quite dramatic.' (Industry Representative 9)

BDM

The composition of BDM was also a major concern. Multiple BDM options are commercially available but precise compositions are not disclosed by mulch manufacturers. The degradability of BDM can be affected by feedstock type and amounts, as well as the minor components incorporated into final mulch products (Anuncdiado *et al.*, 2021*a*). Therefore, most BDM will perform differently and degrade at varying rates because of variations between field sites such as the weather (e.g., air temperatures, rainfall) and soil properties (e.g., soil temperature, pH, moisture content, microbial community composition and activity). Given this, there was some ambiguity among the participants regarding what is really occurring below the soil surface. As one research and outreach specialist stated:

> 'You know again pure speculation on my part, but if the BDM degrades in the soil is that leading to other issues … you know as the compounds are being released could that be attractive for pests?' (Research and outreach specialist 1)

Studies suggest that BDM degrades over time, but there is also a risk that if BDM breaks down slowly under the climatic conditions of western Washington that it could potentially affect soil health (Sintim *et al.*, 2020; Griffin-LaHue *et al.*, 2022). Similar to PE mulch, additional sources of hidden risks included effects on soil microorganism communities and presence of micro-plastics in soil, including their possible translocation into nearby ecosystems.

Esthetics

The appearance of a production system to the agricultural community or other individuals was not associated with a particular type of risk studied in previous literature. However, it was a concern that was expressed by several participants. This concern is associated with the concept of 'good farming' in which growers determine if a production system is culturally appropriate based on the appearance of the farm. Dentzman and Goldberger

(2020) investigated how this concept applied to the use of PE mulch and BDM in different specialty cropping systems. Findings from their study showed that an untidy appearance can negatively impact and prevent adoption of BDM due to their 'plastic,' 'messy,' or 'trashy' esthetic. The esthetics of PE mulch was not as concerning to many of the participants in this study, but it was more frequently noted for BDM. There are many BDM options available in the market and the performance of each plastic mulch is often variable between products. Mulch properties and environmental conditions affect BDM deterioration and in-soil degradation rates (Anunciado *et al.*, 2021*b*). These factors can vary by location and even years, therefore how 'messy' a BDM appears in a field can be difficult to anticipate. In our study, growers indicated that the 'plastic' appearance bothered them, and the unsightly appearance of BDM as they deteriorate impacts adoption decisions. Two growers emphasized:

> 'I'm concerned about agriculture in our community. I'm concerned with some public perception. Plastic is frowned on by a lot of people in our society because it probably [won't be] disposed of properly or handled properly, and then it becomes somebody else's problem and it's the community's problem.' (Grower 2)
>
> 'Blowing off, trash in the field … trying to keep the fields clean … But we're very picky. We don't like leaving plastic anywhere … The esthetics of it is very important.' (Grower 7)

Few research and outreach specialists elaborated on the importance of BDM esthetics in relation to adoption and expressed that growers prefer their farms to appear tidy. The appearance of deteriorating or degrading BDM not only impacts the perception by the community of a farm operation but also increases the concern of having plastic fragments migrate to neighboring properties or waterways. As one research and outreach specialist stated:

> 'Esthetics is probably a barrier, or a limitation based on the work that we did. When that mulch does start to fall apart, it blows around, it gets caught up in the plant material, and the growers don't like that. Messy. It just doesn't look good.' (Research Specialist 1)

None of the industry representatives, however, considered esthetics to be a limiting factor to the use of BDM in raspberry systems. Industry representatives may be more accepting of a 'messy' appearance because they believe in the design and purpose of BDM. However, longer-term studies analyzing the impact of BDM in production systems are limited. If over time research findings demonstrate that BDM is truly more sustainable than PE mulch, it is possible for the agricultural community to become more accepting of its appearance.

Risks not mentioned

Several types of risk were not mentioned by the study participants: financial, human, institutional, and asset risks. The decision to incorporate PE mulch or BDM in a raspberry production system does require an investment ($300–780 and $600–1800 per hectare on average for PE mulch and BDM, respectively) (Zhang *et al.*, 2017), but the cost is considered relatively low and thus the investment is not directly influenced by how a grower decides to obtain or finance capital for their operation. This type of risk would be present through unexpected changes with interest rates or credit conditions, thus it was not applicable in this case.

Sources of risk that would fall under the human category were not discussed by the participants as well. The use of PE mulch and/or BDM do not appear to pose an obvious risk to the overall well-being or personal relationships of individuals involved in a production system because their application, removal, or tillage does not pose high levels of danger. Additionally, plastic mulch use has been shown to help reduce the number of chemical fertilizers and herbicides utilized in various production systems (Steinmetz *et al.*, 2016), demonstrating that it can benefit growers and farmworkers.

Institutional sources of risks did not seem to be a concern, although current policies regarding plastic mulch can pose barriers to adoption. PE mulch is currently approved for use in certified organic and conventional systems and can be applied during soil and bed preparation in conjunction with preplant soil fumigation. At present there are no regulations established by formal or informal institutions that prohibit or limit its use or which, may affect its purchase price. This was reflected in this study as the participating groups did not associate any source of institutional risk to PE mulch use. In contrast, BDM is allowed in organic production systems, although no commercial products currently meet all the criteria established by the U.S. Department of Agriculture's National Organic Program (NOP) (Miles *et al.*, 2021: rule §205.2). While the processed raspberry industry in the region primarily operates using conventional practices, one grower believes that 'it's a tool that has a wonderful fit for the organic system' (Grower 2). Most BDM research is focused on its use in conventional production systems rather than organic. This is due to the strict NOP regulations whereby organic certification would be lost if a prohibited product is applied to a field site. Transitioning and operating land to become organically certified takes much work and time for growers, therefore it is a consequence that many organic growers are unwilling to take. At this time, it may also not be a priority for stakeholders involved in the processed raspberry industry, which was supported by several study participants. One industry representative mentioned: 'There's not much advancement in terms of … for the organic growers, let's say to push the people to using it, and [institutions] to approve it [for organic production].' (Industry Representative 10) Moreover, a few research and outreach specialists mentioned that BDM does not qualify for buffer zone reduction credits, which are important for emission reduction in fumigated systems (DeVetter and Stanghellini, 2020) and may limit their application in conventional raspberry production systems. Unlike PE mulch formulated to have reduced permeability (e.g., totally or virtually impermeable plastic mulch, or TIF and VIF, respectively), BDM has not been openly tested for permeability according to the active ingredients in soil fumigants and the U.S. Environmental Protection Agency has not listed BDM as adequate to reduce fumigant emissions and exposure. While this was not a source of institutional risk, it is an important factor to consider particularly in raspberry production systems where soil fumigation is an important practice used to suppress pressure from soil-borne pathogens and plant parasitic nematodes (DeVetter *et al.*, 2022).

Lastly, sources of asset risk were not a concern among our study participants, possibly because the use of plastic mulch in specialty crop production has been shown to have positive effects on crop productivity by positively modifying the soil and canopy environment as well as plant physiology, and reducing pest and disease pressure (Hammermeister, 2016; Lamont, 2017; Zhang *et al.*, 2021). This risk type is based on the loss of crop due to damage or unexpected events such as theft and fire, which have not been associated with the use of plastic mulch.

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Uncertainty

PE mulch

Uncertainty was also assessed as the study participants were asked about the factors that they considered before making the decision to use PE mulch or BDM. Most growers only had experience with PE mulch and uncertainty revolved around the optimal timing of mulch removal, the most effective way to implement fertilizers, the impact of irrigation, how PE mulch would affect root development, and soilborne pathogens. Research and outreach specialists, as well as industry representatives, did not report any uncertainties related to PE mulch, likely because there is a lot of information available about their incorporation in other production systems (Kasirajan and Ngouajio, 2012).

BDM

Because growers in this study had limited exposure to BDM, they expressed only minimal uncertainties. However, a grower with previous experience using BDM stated that uncertainty about BDM revolved around BDM degradability and future effects in soils and surrounding ecosystems. This grower expressed the following:

> 'I don't know that a lot of our growers have the confidence, they haven't used the product, and I still don't. I'm not sure how completely the product really has broken down. How many years does it really stay in the soil? Over time that's a huge variable. Are there still micro- or nano-plastics in the soil that are still a plastic? Is it really, truly gone and taken into [microbial] biomass? Is there some longer-term negative impact in the soil or the microbial populations in the soil?' (Grower 2)

All research and outreach specialists echoed these concerns and had related questions about using BDM. Their uncertainty revolved mostly around how long it would take for a BDM to completely degrade in western Washington and the impact on 'soil health,' 'microbial communities,' 'plant growth,' and 'macro- and microplastics.' One research and outreach specialist stated:

> 'For perennial growers, how long is it going to last when it fragments and is it going to contribute to groundwater pollution or soil pollution? I think those are some of the main questions.' (Research and Outreach Specialist 5)

Uncertainty about BDM incorporation in raspberry systems, however, was low among industry representatives. Nearly all industry representatives felt strongly that BDM could be a sustainable replacement for PE mulch and emphasized that the next step was to provide research information to growers about its long-term effects. One industry representative stated:

> 'So now, the question is for sure … [what] is left is, what is the impact on the environment?' (Industry Representative 10)

However, it is important to note that all industry representatives have an affiliation to major BDM distributors and thus may generally be more inclined to support BDM over PE mulch. Further, these industry representatives may be more knowledgeable about BDM and aware of the use and impacts of using BDM with other crops. Industry representatives acknowledged that in raspberry production systems they need a BDM that will last long enough to help with the establishment of TC plants, which is approximately 18–24 months (Zhang *et al*., 2020*a*). Therefore, many BDM products designed for the shorter production seasons of annual vegetables will likely not meet those needs. Some industry representatives mentioned that they are in the process of producing a BDM that would support the needs of raspberry growers. Nevertheless, growers and research and outreach specialists still have questions about the degradation process in soil and if there are negative consequences associated with the use of BDM. Until more information is available to address these uncertainties, incorporation of BDM in raspberry production systems may be delayed.

Discussion and conclusion

Agricultural production systems make up one of the largest and most important sectors in the global economy. Exposure to risk is among the highest in agriculture compared to other businesses, but these concepts are not always accounted for in the decision-making process of technology adoption. To account for this, the different types of risk and uncertainties involved in the decision to incorporate PE mulch and BDM into raspberry production systems were assessed by learning about the experiences, attitudes, and opinions of stakeholders involved in the use, research, manufacturing, and distribution of these products. Given that plastic mulch is not traditionally used in raspberry production systems and adoption has increased steadily, it was necessary to gain a deeper understanding of the factors considered during the adoption process as well as the related questions that need to be answered.

Findings from this study demonstrated that adoption of plastic mulch in the case of the processed raspberry industry can be affected by multiple barriers and risk types. For PE mulch, the high upfront and end-of-season costs compared to growing raspberry in a nonmulched system can be barriers to adoption by growers that may not have the capital or resources to transition to a plastic mulch-based system. Barriers for BDM adoption also included high purchase cost as well as current policies that restrict their use during soil fumigation and in organic systems. The 'messy' esthetic of deteriorating or degrading BDM may reduce their application in raspberry systems. Risk was also present and found in various forms such as production, price, and hidden risk (Table 1). Not all risk types present in the literature were discussed by the study participants. Sources of financial, human, institutional and asset risks did not seem to be a concern to growers, research and outreach specialist, and industry representatives.

Overall, PE mulch was perceived to be less risky to the majority of growers and research and outreach specialists due to its 'proven' effects on crops. BDM was considered risky by almost all participants mainly due to the uncertainty about their durability, degradability under field conditions, and the unknown effects they can impose on the environment if they do not perform as designed. Several statements made by industry representatives highlight that the ambiguity related to BDM is partly due to how information about BDM is distributed. Growers trust their mulch suppliers, therefore the supplier should be aware of the regulations associated with BDM and have knowledge about the best methods to apply BDM in the field, as well as the factors that influence durability and biodegradation. Growers may be hesitant to try BDM and may not consider BDM if they are given a product that is not suitable for their production system or a product that is not truly biodegradable. Moving forward with the application of PE mulch and/or BDM will require time to allow for additional research, but also effort to disseminate information to a wider agricultural audience.

Findings from this study are significant to identify risk management strategies for the adoption of PE mulch and/or BDM in raspberry production systems and can be applied to other perennial systems that may benefit from plastic mulch application. Gaining a deeper understanding about risks and uncertainty in the adoption process will also help institutions understand and pass policies that are helpful to reduce the barriers and risks that growers face each season. This investigation will also contribute to the limitations of risk and uncertainty literature. Evaluating how these elements are present in the decision-making process of adoption may highlight important components that are not typically considered when researching and distributing information about new technologies from a horticultural, economic, or business perspective. As mentioned previously, every action has a risk and the consequences may be partially known, or completely unknown. New technologies may provide short-term horticultural benefits, but it is important to consider them alongside the potential future impacts that can affect the environment and economic well-being of our production systems.

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