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Hydromulch Suppresses Dicot but Not Monocot Weeds and Maintains Yield and Fruit Quality in Established Blueberry

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Abstract. **Woven plastic mulch ("weedmat") is widely used in northern highbush blueberry (*Vaccinium corymbosum*) production due to its capacity to suppress weeds, improve soil microclimates, and increase yields. However, weedmat and other mulches made with nonbiodegradable plastics are difficult to recycle, resulting in large amounts of plastic waste being landfilled. Complete removal of plastic mulch from fields is challenging, resulting in macro- and microplastic contamination of agricultural soils and the surrounding agroecosystem. Although soil-biodegradable plastic mulches address many of these issues in conventional agriculture, no commercially available product meets the criteria of the US Department of Agriculture National Organic Program. Hydromulch is a closed-loop, sprayable, biodegradable mulch technology that could provide a sustainable alternative for organic growers while preserving the horticultural benefits of plastic mulch. However, research on hydromulch efficacy in perennial systems is scarce. The objective of this experiment was to ascertain the effects of multiple hydromulch formulations on weed and whip suppression, yield, fruit quality, tissue nutrient status, and seasonal durability [measured as percent soil exposure (PSE)] in an established planting of 'Valor®' northern highbush blueberry cultivated in a dry climate. Two hydromulches formulated using a singular cellulosic feedstock with or without a 4% guar gum were compared with a weedmat control in 2023 and 2024 in a dry climate. Hydromulch formulations had a significantly greater number and biomass of monocot weeds when compared with weedmat due to higher levels of seasonal mulch deterioration. Yield and fruit quality in hydromulch treatments were similar to the weedmat, although the 4% guar gum treatment had a slightly lower yield relative to the no tackifier hydromulch treatment in 2023. Statistically significant but inconsequential deviations from leaf tissue nutrient standards for Eastern Washington were observed but were not attributed to hydromulch treatment. This study illustrated that the evaluated hydromulch formulations suppressed dicot but not monocot weeds while maintaining yield and fruit quality in an established blueberry field. Future hydromulch research should focus on increasing its physical and mechanical properties to enhance monocot weed suppression, the cost-benefits of hydromulch adoption, and understanding any soil health implications of hydromulch use.**

Weed management is a challenge for organic production of highbush blueberries (*Vaccinium corymbosum* L.) in the Pacific Northwest (DeVetter et al. 2015). Application of sawdust or spunbound weedmat are two common strategies to manage in-row weeds in organic fields (Julian et al. 2012; Strik and Vance 2016; White 2006). Spunbound weedmat (herein referred to as "weedmat") is a particularly popular material made by taking small polyethylene and sometimes polypropylene plastic strips and tightly interlocking them to create a weed barrier meant for perennial cropping systems. Hand weeding and organic herbicides are also used, but are costly, with organic herbicides also suffering from limited efficacy (DeVetter et al. 2015). Although plastic mulch technologies, such as weedmat, are a beneficial technology for modern agriculture due to their ability to suppress weeds, optimize soil microclimates, and improve crop yields, they come with increasing sustainability and environmental concerns (Amare and Desta 2021; FAO 2021; Li et al. 2018, 2022; Liu et al. 2014; Madrid et al. 2022). Plastic mulch can rip and tear during crop production and mulch removal at the end of the season, leaving macro- and microplastics in field soils (Li et al. 2022). Resultant plastic mulch fragments have been shown to accrue in the soil's upper horizons and may migrate deeper into soils, water systems, and contaminate the air (He et al. 2018; Li et al. 2022). These microplastic pollutants can bioaccumulate in organisms and have been found in human brain tissue, store-bought produce, and both animal- and plant-based proteins (Conti et al. 2020; Kaushik et al. 2024; Milne et al. 2024; Traylor et al. 2024). These findings elevate concerns surrounding the use of plastics in society, including within agricultural systems. In addition to concerns surrounding environmental contamination and bioaccumulation in living systems, agricultural plastic waste suffers from poor end-of-life management due to how challenging it is to recycle. These challenges are primarily caused by the amount of soil and plant debris (30% to 80% by weight) adhered to plastic mulch when it leaves a field (Ghimire and Miles 2016; Jones 2018; Levitan and Barros 2003; Madrid et al. 2022; Sarpong et al. 2024; Steinmetz et al. 2016). The intersection of these factors results in plastic mulch being landfilled, burned, stockpiled, or buried on farms (Goldberger et al. 2019; Moore and Wszelaki 2016).

Organic growers in the United States are particularly dependent on plastic mulch because of the lack of National Organic Program (NOP)-approved products for effective weed management. Although northern highbush blueberry production is generally less reliant on plastic mulch when compared with many other crops, organic blueberry producers are unique in that they depend on plastic mulch due to the limited availability of effective certified organic herbicides. Ironically, organic growers and consumers often place a premium on sustainability, creating an opportunity for new, more environmentally friendly technologies to succeed (Leonidou et al. 2022). Although soil-biodegradable mulches (BDMs) have begun to help alleviate this issue in conventional agriculture, these films are currently not allowed in organic agriculture due to the NOP prohibiting any BDM whose constituents are not 100% biobased, as determined by ASTM D6866 and outlined in NOP rule §205.3. Currently marketed BDMs miss this criterion by a large amount, given the biobased content at the time of writing ranges from 10% to 40% (Giannotti 2017; Miles et al. 2017; OMRI 2015). Other standards outlined under NOP rule §205.3 are met by some commercially available BDMs. These include BDMs meeting compostability specifications (i.e., ASTM D6400, ASTM D6868, EN 13432, EN 14995, or ISO 17088) and degrading at least 90% within 2 years of incorporation based on ISO 17556 or ASTM D5988 standards (Novamont n.d.; Tosin et al. 2019; USDA 2024a); however, BDMs made with genetically modified organisms are banned per NOP rule §205.601(b)(2)(iii) (USDA 2024b). At the time of writing, no commercially available BDM meets all of these requirements. However, many public and private teams are working on developing a BDM that meets current NOP standards.

A growing focus for researchers wanting to create an alternative technology to plastic mulch is hydromulch (also known as "hydramulch"). Hydromulch is a sprayable alternative to plastic mulch that can be made from 100% biobased feedstocks and additives, making it suitable for use on certified organic farms. Primarily composed of cellulosic polysaccharide feedstocks, the three main ingredients of many hydromulch formulations are cellulose, water, and a tackifier or other bonding agents. Because of its widespread availability, paper is one of the most common cellulosic feedstocks used in hydromulch research. However, not all paper sources are acceptable to the NOP, as virgin paper and paper containing glossy or colored inks are banned per NOP rules §205.601 and §205.2, respectively (USDA 2024b, 2024c). Many potential cellulosic feedstocks could act as fillers and reinforcing agents, including certified organic agricultural residues, such as wheat (*Triticum aestivum* L.) straw (Claramunt et al. 2020). Hydromulch potentially addresses all the sustainability and certification hurdles outlined previously but needs to maintain the horticultural benefits of plastic mulch to be adoptable within commercial organic farms.

Minimal research has been done on hydromulch in diverse agricultural systems. However, "hydroseeding" (i.e., a method of applying seeds, mulch, and sometimes fertilizer through spray), which precedes hydromulch, has been used commercially for bank stabilization and turfgrass establishment since the 1960s, as well as in ecological restoration since the 1970s (Lum et al. 1967; Naveh 1975). Note that although untested at the time of writing, most commercially available hydroseeding substrates are unlikely to be suitable for hydromulching applications because of the formulation often containing compounds that promote seed germination and growth. Granatstein et al. (2002) were among the first to investigate hydromulch in food production and reported effective weed suppression in a greenhouse and field trial with corn (*Zea mays* L.). A short time later, researchers found that hydromulch composed of newsprint, cotton (*Gossypium* spp.) waste, gypsum, and a proprietary adhesive successfully suppressed a wide variety of broadleaf and grass weed species in bell pepper (*Capsicum annuum* L.) and muskmelon (*Cucumis melo* L.). However, the hydromulch struggled to suppress purple nutsedge (*Cyperus rotundus* L.) (Warnick et al. 2006a). An additional unplanted trial conducted within both conventional and organic farms produced similar results (Warnick et al. 2006b). More recently, the inability of hydromulches to suppress nutsedge was re-emphasized in a pot experiment. These studies found that paper-based hydromulches containing filler materials of wheat straw, used mushroom substrate, or rice (*Oryza sativa* L.) husks effectively suppressed 87.5% of dallisgrass (*Paspalum dilatatum* Poir.), but only 16.3% of purple nutsedge sprouts were suppressed. Bermuda grass [*Cynodon dactylon* (L.) Pers.] and Johnsongrass [*Sorghum halepense* (L.) Pers.] exhibited intermediate suppression of roughly 50% (Mas et al. 2021, 2024). Using hydromulch formulations similar to those in Mas et al. (2021, 2024), separate field trials demonstrated that hydromulches effectively managed annual broadleaf weeds in various perennial cropping systems, including almond [*Prunus dulcis* (Mill.) D.A.Webb], peach [*Prunus persica* (L.) Batsch], and artichoke [*Cynara cardunculus* var. scolymus (L.) Fiori]; however, hydromulch was ineffective against perennial weeds such as purple nutsedge and field bindweed (*Convolvulus arvensis* L.) (Cirujeda et al. 2024). In addition Puka-Beals and Gramig (2021) found that hydromulch suppressed weeds in carrot (*Daucus carota* L.) at rates similar to mulch made of two parts weed-free composted manure to one part hemp (*Cannabis sativa* L.) hurd (termed "compost blankets"). Ahmad et al. (2024) and Weiss et al. (2025) demonstrated that in annual strawberry (*Fragaria* ×*ananassa* Duchesne ex Rozier 'Albion') systems, hydromulch containing 6% tackifier produced fruit quality and yields comparable to polyethylene (PE) mulch films despite slightly greater weed pressure in hydromulch treatments. Although few studies have examined hydromulch performance in perennial cropping systems, a promising example is the evaluation of Cline et al. (2011) in irrigated apple (*Malus domestica* Borkh.) orchards, whereby hydromulch was identified as a potential alternative to glyphosate because it effectively suppressed weeds while enhancing tree vigor.

The objective of this experiment was to evaluate the performance of various hydromulch formulations relative to plastic mulch ("weedmat") in an established northern highbush blueberry planting within a dry climate. Specific variables that were monitored included weed and whip suppression and seasonal mulch durability. In addition, various plant production metrics including yield, fruit quality, and tissue nutrient status were recorded. Resultant information from this trial will aid in the development of hydromulch as an alternative to nonbiodegradable plastic mulch for conventional as well as organic producers striving to reduce their plastic footprint while maintaining the horticultural benefits provided by plastic mulch.

Materials and Methods

Site characteristics. A 2-year field experiment was conducted during the 2023 and 2024 growing seasons in a 5-year-old certified organic northern highbush blueberry field using the cultivar Valor®. The experiment was located near Prosser, WA, USA (lat. 46°12′22.6″N, long. 119°46′06.6″W). The area is classified as cold semiarid (BSk) under the Köppen-Geiger climate classification system, characterized by hot-dry summers, cool winters with freezing temperatures, and occasional precipitation (Beck et al. 2018). The soil at this location is a silt loam characterized as mixed, superactive, mesic Xeric Haplocambids (NRCS Soil Survey Staff 2024). The slope ranges from 0% to 2%, with a thin mantle of loess over lacustrine or glaciolacustrine deposits. The grower planted the field in 2018, 5 years before trial establishment. The grower used a mechanical bed shaper to create beds with a target base width of 1.2 m. However, at trial establishment on 28 Mar 2023, base bed width ranged from 1.1 m to 1.2 m due to erosion of bed shoulders from weathering combined with farming practices such as mowing. Bed height was 0.3 m, and row length for the entire field was

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Data will be available on the USDA Ag Data Commons website: https://agdatacommons.nal.usda.gov/ and available upon request to the corresponding authors.
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580 m. Dual drip tube lines were installed on the surface of raised beds after bed shaping and were ~0.4 m apart on either side of the blueberry bushes. Two pieces of weedmat mulch (woven polypropylene and PE plastic groundcover) were installed over the drip tube with a seam running down the middle. Weedmat was snug around the base of bushes to prevent weed growth, secured using plastic stakes, and the edges were buried in the alleyway. A two-wire trellising system was installed during planting establishment and bushes were trained on this system.

Experimental design. This trial used a randomized complete block design with four replicates. Four mulch treatments were evaluated in 2023 whereas only three treatments were carried forward, evaluated in 2024, and presented in this study because of logistical problems associated with one of the treatments (further details provided later in this article). Replicates were 48.8 m long and began 12.2 m from the edge of the field to avoid edge effects. Replicates were divided into four 12.2 m long plots, and one of the four mulch treatments was randomly assigned to each plot. Data were collected only on the interior five to seven bushes, leaving two bushes on either side of the plot as a buffer between adjacent plots, totaling 9 to 11 bushes per plot. The exception to this was in 2024 when yield data were measured from whole plots that were machine harvested, making it impossible to exclude buffer areas.

Treatment application. Two hydromulch treatments were compared with a weedmat control to evaluate in-field performance of hydromulch. Mulch treatments included 1) bogus paper with 4% guar gum tackifier (4% guar gum with 129.7 paper: 3.8 L water); 2) bogus paper with no tackifier (135 g bogus paper: 3.8 L water); and 3) a weedmat (control). Abbreviations for each treatment include 4% guar gum, no tackifier, and weedmat, respectively. The choice of paper feedstock, ratio of paper to water, and tackifier percentage were based on prior research that evaluated hydromulch material properties and in-field performance (Ahmad et al. 2024; Durado et al. 2024; Weiss et al. 2025). Treatments using bogus paper as the cellulosic feedstock used ULINE recycled bogus paper rolls (S-11424; Uline, Pleasant Prairie, WI, USA) with a basis weight of 226.2 g/m^2 and a paper thickness of 150 μm. A fourth treatment composed of a slurry obtained from an apple packing plant was evaluated in the first year but not advanced for additional trialing. The slurry consisted of water, sodium hydroxide (NaOH), and recycled paper and was applied at a rate of 8852 kg dry matter per hectare. The difference in dry matter between this treatment and others was unavoidable due to the slurry material being 15% less paper by volume, and transport tank limitations not allowing us to transport the extra 15% from the packing plant to the field site. Although the slurry treatment was not carried forward into the second year of the experiment due to logistical and upscaling concerns, 1 year of data are included in the US Department of Agriculture's (USDA's) AgDataCommons database entry associated with this project, as to contribute information on this particular hydromulch source. All materials were approved by the on-farm cooperator's organic certifier, as certifier approval for any new products applied is critical for maintaining certified organic status.

A custom-built hydromulch applicator (Fig. 1) fabricated at the Washington State University (WSU) Northwestern Research and Extension Center in Mount Vernon, WA, USA, was used for hydromulch applications. Parts of the system include a flextube, a 2.5 cm 80° brass flat fan spray nozzle with 219.6 maximum liters per minute (VeeJet type nozzle with custom aperture), a 78.7 cm × 104.0 cm stainless-steel platform with a 3-point hitch, 5.1 cm polyvinyl chloride (PVC) tubing, and two 5.1 cm PVC valves. Power for the system was supplied by a 212 cm^3 gasoline semitrash water pump (Predator™ 63405; Harbor Freight Tools®, Calabasas, CA, USA). In 2023, a 208 L blue plastic barrel (Fig. 1A) (S-10757; Uline) was used to contain the hydromulch slurry. This container was undersized for the task and posed logistical challenges during application, so for the 2024 season a 246 L agricultural storage tank was used (Fig. 1B) (Norwesco White Vertical Storage Tank 45192; Norwesco, Boulevard Mound, MN, USA). The hydromulch applicator used a dual recirculation loop, with the primary loop for recirculation and application and the secondary loop for continuous recirculation to prevent paper settling and pump clogging. The secondary loop also created a space for a secondary valve, critical to fine-tuning hydromulch output rate and pressure.

The bogus paper used in the no tackifier and 4% guar gum treatments was first prepared by shredding paper rolls using an office-style paper shredder (Bonsaii® EverShred c149-d; Bonsaii®, Flowery Branch, GA, USA). To prepare the bogus paper feedstock, either 4.7 kg (no tackifier) or 4.5 kg (4% guar gum) of shredded paper was placed into garbage cans with 132.5 L water. The paper was pulped by blending with a drill (D130V; DeWalt, Towson, MD, USA) and a drywall mixing attachment (75001Q; Q.E.P Co., Boca Raton, FL, USA) until a semihomogeneous mixture was formed. The resultant mixture was then pumped into the hydromulch applicator's tank until the tank was full. Following this, the mixture was circulated for several more minutes to break down the paper into a homogeneous mixture. Guar gum tackifier was then added to achieve a 4% concentration for tackifier containing treatments, and the mixture was recirculated until the tackifier was evenly incorporated throughout the mixture.

Treatment applications were completed on 25 Apr 2023 and 2 Apr 2024. These dates were chosen to prevent the hydromulcher from knocking flowers off bushes as it moved through the field. In 2024, the same hydromulch treatments were re-applied over the material applied in 2023, making treatment application consistent between years. The application was completed by driving a tractor in the alleyway next to the blueberry bushes, with a person walking behind to aim the nozzle at the bed (Fig. 1C). Because of equipment limitations, two passes were required to complete the application at a rate of 8852 kg dry matter per hectare and a target thickness of 2 to 7 mm. Weedmat was already in place, so no additional application was needed for the control.

Plant management. Blueberry bushes were maintained using standard organic practices specific to the cooperating farm, which are unavailable for public disclosure. Management included the use of drip tubes with fertilizer injection, heat mitigation using microsprinklers, frost mitigation from fans and propane burners, mowing of alleyways and shoulders, trellising, and annual pruning. Weeds were periodically managed using capric and caprylic acids (Supress EC; San Agrow, Chelsea Vista, CA, USA). The grower cooperator carried out all pest and disease monitoring, and any action taken to address pests or diseases in the field aligned with certified organic practices.

Mulch performance data collection. Mulch performance was evaluated by quantifying blueberry whip and weed number, weed shoot biomass, and mulch deterioration within permanent subplots measuring 1 m long and spanning the width of the bed from shoulder to shoulder (1.2 m^2). Whip, weed number, and weed biomass are cumulative for each year. Whips are vigorous, upright-growing shoots that emerge near or on the crown or from older wood on blueberry bushes. New whip growth is an important component of blueberry production, as new whips are required to replenish fruiting canes and maintain the architecture of the plant (Pritts et al. 1992). However, not all whip growth is positive, and some whips are unwanted due to their growth being too far away from the crown of the plant. These unwanted whips, commonly called "suckers," may take vigor away from the rest of the bush, block light penetration to below canopy fruit, produce minimal fruit, and weaken overall bush structure while complicating machine harvest operations (Pritts et al. 1992). Whip number was measured by counting the number of whips (<1-year-old shoots) within 10 cm of the base of the crown; whips emerging higher than 10 cm above the base of the crown (<10 cm above the base of the crown) were not counted, as these are the whips that may become future fruiting canes. Weed number was determined by counting the number of visible weeds in each subplot. PSE was visually estimated as ratings made from one side of the bed. A PSE rating of 0% represented a fully intact mulch layer, whereas a PSE rating of 100% signified complete deterioration and full soil exposure. Assessments were made in 1% increments until 20% PSE and 5% increments thereafter (Cowan et al. 2014; Wang et al. 2022). All whip and weed count as well as PSE data were recorded at the beginning of each month from April to September in 2023, April to October in 2024, and were about aligned with the first of each month.

Weed shoot biomass was collected during peak vegetative emergence on 25 Jul 2023

Fig. 1. Custom-built hydromulch applicator with original 208-L storage tank (from tractor side) (**A**), the applicator with newer 246-L storage tank (**B**), and hydromulch being applied to one side of a blueberry bed (**C**).

and 7 Aug 2024. Shoot biomass samples were collected by clipping all weeds inside the subplots at the soil surface, placing different weed taxa into separate paper bags labeled by plot, and drying at 38 °C until a constant weight was achieved, and then weighing. All weed data were categorized as monocotyledonous or dicotyledonous (i.e., monocot or dicot, respectively) and further identified to the lowest taxonomic rank possible. Note that grasses could not be reliably identified beyond genera because of a lack of flower/seed development before biomass harvest.

Yield and fruit quality data collection. Yield data were collected by hand harvesting berries from five interior bushes per plot in 2023. In 2024, the grower shifted to using an over-the-row machine harvester and all bushes were harvested within a plot. Both years, harvest data were divided by the number of bushes from which berries were collected to calculate yield per plant. Harvests occurred on 24 Jul 2023 and 23 Jul 2024. Harvested berries were stored no more than 36 h at 4.4 °C, and firmness was measured using a 50-berry subsample of marketable, undamaged berries. Firmness measurements were performed within 36 h of harvest using a FirmTech II (Bioworks Inc., Columbus, OH, USA) set to maximum and minimum compression forces of 250 g/mm and 25 g/mm, respectively. Samples were then frozen at −23 °C until further fruit quality analysis was performed.

Fruit quality analysis was initiated by defrosting berries at room temperature (~21 °C). Juice was extracted by placing berries into three layers of cheesecloth and squeezing by hand until 50 mL of juice, free of visible solids, was obtained. Juice sugar content (measured as °Brix), pH, and titratable acidity (TA; as percent citric acid) were then measured in triplicate. °Brix was measured using a digital refractometer (HI96801; Hanna Instruments, Smithfield, RI). Before TA analysis, initial juice pH was measured using an ATAGO pH meter (PAL-pH 4311; ATAGO, Minato-ku, TYO, JP). TA was analyzed by titrating juice to a pH of 8.1 using 0.1 N sodium hydroxide and a digital titrator (HI84532; Hanna Instruments, Smithfield, RI, USA).

Leaf tissue nutrient content. Taking care not to sample from whips, the most recent fully expanded, disease-free leaves were sampled from chest height lateral shoots. Samples were taken on 16 Aug 2023 and 8 Aug 2024, respectively, the ideal time for leaf tissue sampling (Lukas et al. 2022). Four leaves were taken per plant, two from either side of the bush, sampling all plants in each plot excluding buffer plants. Leaves were oven dried at 60 °C for 48 h and samples were sent to Brookside Laboratories (New Bremen, OH, USA) for macro- and micronutrient analysis. Methods for nutrient content determination were drawn from the Soil, Plant, and Water Reference Methods for the Western Region

Table 1. Average monthly air temperature, total precipitation, and relative humidity near the hydromulch experiment location in Prosser, WA, USA, 2023 and 2024. Data were collected from a Washington State University AgWeatherNet station 11.6 km from the experimental field location.

	April	May	June	July	August	September	October
2023							
Average temperature (°C)	10.3	18.4	19.7	23.0	21.4	16.4	10.5
Total precipitation (mm)	19.3	11.9	5.1	2.0	6.6	6.6	6.6
Relative humidity (%)	57.6	57.7	54.6	52.4	66.2	73.6	84.8
2024							
Average temperature (°C)	10.7	14.8	19.1	23.9	20.8	18.4	10.6
Total precipitation (mm)	7.6	5.8	4.8	0.0	0.3	0.0	11.9
Relative humidity (%)	55.3	51.3	45.1	48.0	61.8	62.6	72.6

(Gavlak et al. 2005; Kingston and Jassie 1986; Sah and Miller 1992). Total nitrogen analysis was completed using a Carlo Erba combustion analyzer (1500 mk I; Carlo Erba, Cornaredo, MI, USA). All other nutrients were analyzed by inductively coupled plasma spectroscopy (Thermo 6500 Duo ICP Spectrometer; SpectraLab, Markham, ON, CA) following microwave digestion with HNO_3 and H_2O_2 in closed Teflon vessels.

Environmental data. Relative humidity, air temperature, and precipitation were measured every 15 min at the nearby Grandview weather station, 11.6 km from the field's location, using a WSU AgWeatherNet station (WSU AgWeatherNet 2025) (Table 1). Data loggers were also used to measure soil temperature and moisture and were installed in the third replicate under the mulch layer. Sensors were installed horizontally at a depth of 10 cm and 5 cm away from irrigation emitters. Per manufacturer instructions, care was taken not to disturb soil above the sensor during installation, as this can negatively impact soil moisture accuracy.

Statistical analysis. Analysis of variance (ANOVA) was completed using the lme4 R [R version 4.3.3 (R Core Team 2024)] package, with mulch treatment and year considered fixed effects and replicate as a random effect (Bates et al. 2015). Response variables were composed of whip and weed number, weed biomass, PSE, yield, fruit quality variables, and individual leaf tissue nutrients. Simple main treatment effects and the interaction between treatment and year were considered significant at $\alpha = 0.05$. In cases in which significant treatment by year interaction(s) were observed, data were further analyzed separately by year. Homogeneity of variances was assessed through graphical analysis, and normality through the Shapiro-Wilk test ($W > 0.90$), both found in base R. Using a least-squares mean option, a two-way ANOVA was performed. Using the emmeans package, a Tukey-Kramer post hoc analysis was used for significance testing and estimates with adjustments for multiple comparisons as needed (Lenth 2024). Because weed number and weed biomass data were not normally distributed, they were analyzed using a nonparametric Kruskal-Wallis test found in base R. Where significant differences were detected, pairwise comparisons were conducted using a Dunn test with a Šidák adjustment. Environmental data were not analyzed statistically due to a lack of replication and all data were averaged by month. The slurry treatment was not statistically analyzed given only 1 year of data were collected and it demonstrated heteroscedasticity that weakened the analysis. Only a general summary of the slurry treatment is included.

Table 2. Mean blueberry whip number, weed number, and weed shoot biomass (g dry matter/treatment) collected within an established 'Valor®' northern highbush blueberry planting treated with various hydromulch (HM) formulations in Prosser, WA, USA. Mean whip and weed numbers are cumulative for each year and biomass data were collected at peak vegetative emergence on 25 Jul 2023 and 7 Aug 2024. Data were determined from 1-m long by 0.34-m base-width subplots.

	Number[i]			Shoot biomass[i]	
Treatment[ii]	Whips (unwanted)	Monocot weeds	Dicot weeds	Monocot (g)	Dicot (g)
2023					
HM, 4% guar gum	20.2 a[iii]	17.4 a	1.0 b	13.9 a	3.1
HM, no tackifier	19.8 a	32.4 a	3.1 a	8.5 a	0.3
Weedmat	2.9 b	0.1 b	0.1 c	0.0 b	0.0
2024					
HM, 4% guar gum	10.0 a	40.1 a	0.7 b	145.9 a	1.5
HM, no tackifier	9.2 a	30.8 a	1.4 a	167.4 a	2.1
Weedmat	8.1 b	0.4 b	0.3 c	1.3 b	7.9
Significance					
Treatment[iv]	<0.001	<0.001	<0.001	<0.001	0.237
Year	0.724	0.645	0.504	0.005	0.427
Treatment × year	ND[v]	ND[v]	ND[v]	ND[v]	ND[v]

[i] Number and biomass data were analyzed nonparametrically using Kruskal-Wallis and a Dunn test due to non-normality.

[ii] Treatments consisted of hydromulch formulations made from recycled paper with either 0% or 4% guar gum and a weedmat control.

[iii] Means with the same letter within a column do not significantly differ due to treatment at $\alpha = 0.05$. A Šidák adjustment was used to account for multiple comparisons.

[iv] Treatment statistics were analyzed across years.

[v] Whip and weed number and weed biomass do not have statistics for location × treatment interactions due to a lack of statistically meaningful nonparametric two-way analysis. ND denotes no data.

Results and Discussion

Mulch performance. Both hydromulch treatments had significantly more whip growth than the weedmat across both years of the trial ($P < 0.001$; Table 2). Hydromulch treatments trended toward having less unwanted whip growth in 2024, indicating that multiple hydromulch treatments may suppress whips better than a single application. An important auxiliary function of mulches in blueberry systems is the suppression of these unwanted whips for high vigor cultivars and plantings and results indicate hydromulch provides poor suppression of whip emergence.

Both hydromulch treatments had a significantly greater number of monocot weeds and monocot biomass when compared with the weedmat (both $P < 0.001$; Table 2). Monocot growth trended toward greater yellow nutsedge (*C. esculentus* L.) populations in 2023 and increased grass communities in 2024 with monocot biomass more than 10 times greater in 2024 compared with 2023 ($P = 0.005$). This increase in monocot biomass across years and trend toward greater grass pressure in 2024 was likely due to different reproductive strategies, with grasses having the ability to reproduce using an abundance of viable seed and yellow nutsedge mainly reproducing rhizomatously while suffering from poor seed viability (Dor and Hershenhorn 2013; Peerzada 2017; Quinn 2000; Stoller 1981; Thullen and Keeley 1979; Tuthill et al. 2023). These differences in reproductive strategy likely allowed grasses to deposit many viable seeds on top of the 2023 hydromulch layer, shifting the monocot population in hydromulch treatments toward grasses in 2024. This result parallels findings from other hydromulch trials in perennial systems, which indicated weed pressure from Asteraceae was increased by hydromulch use (Cirujeda et al. 2024).

In contrast to monocots, the 4% guar gum treatment had a significantly lower number of dicot weeds than the no tackifier treatment, and the weedmat had significantly fewer dicots than both 4% guar gum and no tackifier ($P < 0.001$; Table 2). The primary dicot species observed was lambsquarters (*Chenopodium album*), an annual forb, and thistle (*Cirsium* sp.), a perennial forb. Dicot weed species were abundant in the alleyways of blueberry fields in the study region, so they are likely to be present in the seed bank. Interestingly, analysis of dicot biomass revealed no significant treatment effect.

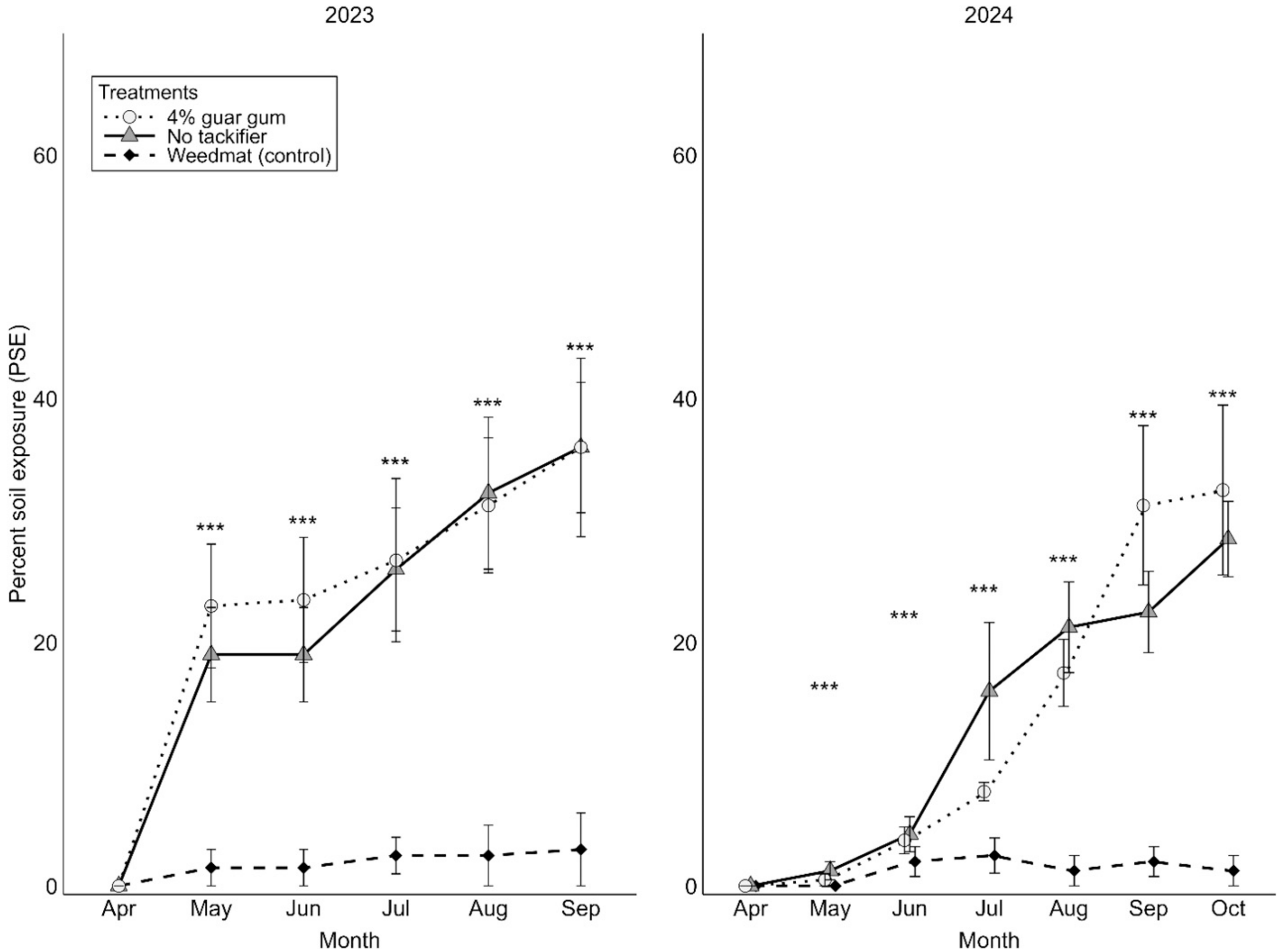

Fig. 2. Percent soil exposure (PSE, %) in plots of 'Valor®' northern highbush blueberry treated with hydromulch with 4% guar gum or no tackifier, relative to a weedmat in a cold semiarid (BSk) climate from Apr–Sep 2023 and repeated from Apr–Oct 2024. Asterisks indicate significant differences among hydromulch and weedmat treatments, with *** indicating $P < 0.001$.

Dicot weed biomass data showed that 4% tackifier, no tackifier, and weedmat all had statistically similar amounts of dicot biomass accrual, and accrual was overall low in comparison with monocot biomass, with the greatest biomass in the weedmat treatment at an average of 7.9 g. Note that a single subplot of weedmat had a pale smartweed [*Persicaria lapathifolia* (L.) Delarbre] plant, which accrued 146.25 g biomass (316% greater than the next dicot biomass); however, when this data point was treated as an outlier and removed there were still no significant differences, and the 4% guar gum treatment trended toward having the greatest dicot biomass across years at an average of 2.28 g.

PSE data are presented by year due to a year by treatment interaction ($P < 0.001$; Fig. 2). In 2023 and 2024, weedmat had significantly less PSE compared with both hydromulch treatments (all $P < 0.001$). In addition, PSE declined from 2023 to 2024 by 8.03%, likely due to the 2024 application being sprayed over residual hydromulch from 2023, increasing the total volume of paper in the field during the 2024 season. The end-of-season PSE (the final data collection each year) between the two hydromulch treatments was not statistically different across years and averaged 34.2% for 4% guar gum and 32.2% for no tackifier treatments compared with 2.1% for the weedmat. PSE is an important measure of mulch durability and persistence under field conditions (Cowan et al. 2014). A good biodegradable mulch should theoretically remain intact long enough to suppress weeds, sustain yields, and preserve fruit quality but be in a condition to biodegrade at the end of the season. An experiment conducted in the same growing environment reported end-of-season PSE for a soil-biodegradable plastic mulch made from Ecovio® feedstock [polybutylene adipate terephthalate (PBAT) and polylactic acid (PLA)] averaged 59% after 2 years of cropping, with no significant impact on strawberry yield or fruit quality, which is greater than the 30.5% PSE measured at the cessation of this trial in 2024 (Wang et al. 2022). Thus, hydromulch displayed nearly half the deterioration of a commercially available soil-biodegradable mulch. Despite these comparatively low PSE values, weed suppression was poor, which may decrease bush performance over time if unsuppressed weeds from hydromulch utilization are not managed through additional measures. Moreover, the poor suppression of weeds stemming from hydromulch PSE values greater than the weedmat suggests the farmer would incur additional weed management costs and that hydromulch, in its current format, is a poor option for weed management in organic blueberry systems, particularly if monocot weed pressure is high. Younger plants, which are more susceptible to weed pressure, would likely establish poorly if the unsuppressed weeds in hydromulch were not managed (Strik et al. 2012).

The hydromulch slurry failed to meet the requirements for our trial and commercial application. This is likely because the treatment contained 15% less paper (w/v) relative to the other tested hydromulch treatments in the trial. As a result, the end-of-season PSE of the slurry treatment was 54%, which is 44% greater than guar gum and no tackifier treatments, and 1692% greater than the weedmat control, relative to other tested hydromulch treatments in the trial (data not presented). While slurry is an appealing treatment because it is pre-mixed and can be repurposed from a nearby tree fruit packing plant, its cost to transport is prohibitively high in most situations. To make a functional hydromulch, the slurry would need to be reformulated with an increased paper-to-water ratio.

Yield and fruit quality. Yield was analyzed by year due to a significant treatment by year interaction ($P = 0.02$; Table 3). Yield in 2023 was greatest from plants treated with hydromulch containing no tackifier, lowest for plants treated with 4% guar gum, and intermediate for the weedmat. However, differences in yield were not observed in 2024. While differences in yield were slight, caution is warranted with commercializing hydromulch application in blueberry systems. Poor weed suppression of perennial species observed in the hydromulch treatments could lead to sustained plant competition over multiple years and a buildup of weedy seedbanks, which in turn may deplete blueberry plants and lead to lower yields over time.

Mulch treatments had no effect on fruit quality (Table 3). The only differences detected were pH and TA being greater in 2024, and berry firmness being lower in 2024 (all $P < 0.001$). Differences in juice pH and TA can be attributed to annual environmental variability and potential variations in crop phenology at harvest. Phenological factors that may influence pH and TA between years include changes in light penetration, harvest timing, and environmental conditions (Lobos et al. 2013, 2014, 2018; Redpath et al. 2021). Berry firmness was notably diminished in 2024 compared with 2023 and can be attributed to the grower's choice to hand harvest in 2023 and machine harvest in 2024. Machine harvesting is known to cause more internal damage to berries than harvesting by hand, decreasing berry firmness for 2024 (Casamali et al. 2016; Takeda et al. 2013).

Environmental data. During several months, soil water content trended toward being lowest for the 4% guar gum treatment, and during 2023, no tackifer trended toward the greatest soil water content with weedmat being a close second (Table 4). Other than the 4% guar gum treatment, soil water content never fell below a monthly average of 0.21 m^3/m^3. This soil water content level was well above the range of 0.11 to 0.16 m^3/m^3 reported in the literature for late season blueberry production (Bryla and Strik 2007). Due to a hole in a drip tube, the 4% guar gum plot that had the soil moisture logger fell far below this mark during Aug 2023 at an average of 0.04 m^3/m^3 and trended toward having lower soil water content compared with all other treatments beginning July of 2023. The hole in the drip tube was repaired in Aug 2023 but the tube continued to have a minor leak for the duration of the trial. While the 4% guar gum treatment trended toward having less soil moisture content than other treatments, the soil moisture level was generally in the range Bryla and Strik (2007) found for highbush blueberry in the region, and no visual symptoms of water stress were observed in any treatment. It is possible, however, that the lower yield observed in the 4% guar gum treatment in 2023 can be attributed to lower soil moisture levels due to drip tube damage. Unlike soil moisture, soil temperature was static across treatments, with no observable trends past seasonal fluctuations (Table 5). Other than May 2024, all soil temperature averages were higher or lower than the ideal range for blueberry root growth of 14 to 18 °C (Abbott and Gough 1987; Spiers 1995; Strik et al. 2020). Values outside the ideal range trended toward being, at most, 3.9 °C below 14 ° and 9.3 °C above 18 °C.

Table 3. Yield and fruit quality [°Brix, pH, titratable acidity (TA; as percent citric acid), and firmness] measured from an established 'Valor®' northern highbush blueberry planting treated with various hydromulch (HM) treatments. Harvests were conducted on 24 Jul 2023 and 23 Jul 2024 in Prosser, WA, USA.

Treatment[ii]	Yield[i] (kg/plant)	Fruit quality[i] °Brix	pH	TA (%)	Firmness (g/mm deflection)
Grand mean					
2023					
HM, 4% guar gum	2.58 b[iii]	14.37	3.20	1.07	171.14
HM, no tackifier	3.91 a	14.21	3.23	1.07	169.84
Weedmat	3.11 ab	14.30	3.27	1.08	175.24
2024					
HM, 4% guar gum	3.17	13.55	3.59	1.14	156.23
HM, no tackifier	3.54	14.97	3.55	1.14	153.12
Weedmat	2.92	14.45	3.46	1.13	144.02
Significance					
Treatment	0.180	0.322	0.107	0.584	0.241
Year	0.896	0.834	<0.001	<0.001	<0.001
Treatment × year	0.020	0.322	0.107	0.584	0.241

[i] Data were analyzed using the least square means analysis of variance and Tukey's honestly significant difference.

[ii] Treatments consisted of hydromulch formulations made from recycled paper with either 0% or 4% guar gum and a weedmat control.

[iii] Means with the same letter within a column do not significantly differ due to treatment at $\alpha = 0.05$. A Tukey adjustment was used to account for multiple comparisons.

Table 4. Average monthly soil volumetric water content under hydromulch (HM) treatments applied to an established 'Valor®' highbush blueberry planting during 2023 and 2024 in Prosser, WA, USA. Soil temperature data were collected using sensors installed at a 10-cm depth from 28 Mar to 15 Sep 2023, and from 31 Mar to 8 Oct 2024. ND denotes no data.

Treatment[i]	Soil water content (m^3/m^3) April	May	June	July	August	September	October[ii]
2023							
HM, 4% guar gum	0.33	0.33	0.28	0.12	0.04	0.15	ND
HM, no tackifier	0.28	0.28	0.26	0.29	0.32	0.33	ND
Weedmat	0.21	0.23	0.24	0.25	0.25	0.26	ND
2024							
HM, 4% guar gum	0.22	0.24	0.18	0.15	0.22	0.24	0.24
HM, no tackifier	0.32	0.32	0.28	0.26	0.33	0.36	0.36
Weedmat	0.29	0.32	0.28	0.29	0.36	0.37	0.37

[i] Treatments consisted of hydromulch formulations made from recycled paper with either 0% or 4% guar gum and a weedmat control.

[ii] October treatments are not available for 2023 due to ground frosting ending data collection in September of that year.

Table 5. Average monthly soil temperatures under hydromulch (HM) and weedmat treatments applied to an established 'Valor®' northern highbush blueberry planting during 2023 and 2024 in Prosser, WA, USA. Soil temperature data were collected using sensors installed at a 10-cm depth from 28 Mar to 15 Sep 2023 and from 31 Mar to 8 Oct 2024. ND denotes no data.

Treatment[i]	Soil temp (°C) April	May	June	July	August	September	October[ii]
2023							
HM, 4% guar gum	10.2	18.5	20.1	23.3	22.7	19.9	ND
HM, no tackifier	10.1	18.7	21.0	23.3	21.6	20.1	ND
Weedmat	10.3	19.1	20.6	23.0	21.4	19.9	ND
2024							
HM, 4% guar gum	11.0	14.6	18.5	21.8	20.8	18.7	13.7
HM, no tackifier	12.7	15.4	18.9	21.8	21.1	18.7	13.6
Weedmat	13.2	16.4	19.4	22.8	21.1	19.0	13.3

[i] Treatments consisted of hydromulch formulations made from recycled paper with either 0% or 4% guar gum and a weedmat control.

[ii] October treatments are not available for 2023 due to frost ending data collection in September of that year.

Table 6. Leaf tissue nutrient concentrations for an established 'Valor®' northern highbush blueberry planting in Prosser, WA, USA. Samples were collected by taking two leaves from either side of the bush (four per bush) from the most recent fully expanded, nonwhip, disease-free lateral shoots on 16 Aug 2023 and 08 Aug 2024.

	Leaf tissue nutrients[i]												
	N	P	K	Mg	Ca	S	B	Fe	Mn	Cu	Zn	Al	Na
Treatment[ii]	(%)						(ppm)						
2023													
HM, 4% guar gum	1.63	0.08	0.33	0.37	1.02	0.13	44.43	146.93	93.65	3.73	9.00	175.85	270.80
HM, No tackifier	1.59	0.08	0.33	0.37	1.04	0.12	44.30	132.63	96.05	3.63	8.93	174.53	288.23
Weedmat	1.64	0.08	0.35	0.37	1.06	0.13	47.93	148.78	114.85	3.98	8.95	184.78	309.90
2024													
HM, 4% guar gum	1.83	0.08	0.31	0.25	0.92	0.13	35.38	111.75	112.68	3.80	10.25	109.45	175.40
HM, No tackifier	1.82	0.09	0.34	0.25	0.92	0.13	38.95	95.70	120.48	4.05	9.58	112.13	190.15
Weedmat	1.89	0.08	0.33	0.25	0.91	0.13	37.33	102.33	108.15	4.23	12.58	117.58	219.85
Significance													
Treatment	0.045[iii]	0.935	0.407	0.979	0.870	0.870	0.601	0.206	0.754	0.244	0.738	0.673	0.090
Year	<0.001	0.081	0.349	<0.001	0.056	0.079	0.001	<0.001	0.193	0.148	0.033	<0.001	<0.001
Treatment × year	0.693	0.381	0.502	0.953	0.793	0.793	0.614	0.778	0.347	0.694	0.850	0.971	0.974

[i] Data were analyzed using the least square means analysis of variance and Tukey's honestly significant difference.
[ii] Treatments consisted of hydromulch formulations made from recycled paper with either 0% or 4% guar gum and a weedmat control.
[iii] Based on the F-test, a marginal significance was present. However, a lack of statistical power inhibits our ability to precisely determine these differences.

Leaf tissue nutrient content. Leaf tissue nutrients had significant variation between years for N, Mg, B, Fe, Zn, Al, and Na. These differences between years is likely due to how tightly grouped data were within each year, and past research in the region has shown that differences are unlikely to be caused by environmental variance between years (Bailey et al. 1962; Strik and Vance 2015). Despite this, no interactions were observed between year and treatment (Table 6). When data were pooled across years, a marginal treatment effect was observed for N ($P = 0.045$), with 4% guar gum averaging 1.73%, no tackifer 1.70%, and weedmat 1.77%. Lower N content for the hydromulch treatments compared with weedmat may have been caused by significantly greater weed pressures and greater monocot biomass observed in the hydromulch treatments (all $P < 0.001$). Lowbush blueberry (*V. angustifolium* Aiton and *V. myrtilloides* Michx.) is a poor competitor for N at high weed densities, especially when competing with grass species, and it is possible highbush is similarly affected (Marty et al. 2019; Penney and Mcrae 2000).

Leaf tissue nutrient results were compared with the current leaf tissue nutrient sufficiency standards for Eastern Washington (Lukas et al. 2022). All responses were within recommended ranges except for N, K, Ca, and Mg. In 2023, leaf N was within the standard range (1.25% N to 1.75% N) and K fell slightly below its standard (0.35% K to 0.65% K), but Ca and Mg were both above the upper limit of the standard (0.40% Ca to 1.00% Ca; 0.12% Mg to 0.25% Mg). In contrast, 2024 leaf N was greater by 0.1%, K was still under by up to 0.04% and both Ca and Mg were within the standard. All values were above or below tissue standards by less than 0.1%, which seems relatively inconsequential. The differences in K, Mg, and Ca likely occurred due to the calcareous nature of Prosser soils, which generally have an abundance of Mg and Ca coupled with low levels of K (Liao et al. 2020).

Conclusions

The formulations of hydromulches used in this study lacked the ability to suppress monocot weed species, even though yield was marginally impacted in only 1 year of this 2-year study and fruit quality was unaffected during the course of the study. Poor monocot weed suppression in hydromulch treatments was attributed to the reproductive nature and growth habit of monocots and greater levels of mulch deterioration, which was 10 times greater compared with the weedmat as measured through PSE. It is also possible that multiyear hydromulch treatments shifted monocot species toward grasses, but further research is needed to confirm this finding. Conversely, hydromulches showed a better capacity to suppress the dicot weed species present in this study with the weedmat still performing significantly better at lowering dicot number. In addition, the 4% guar gum treatment had a significantly lower number of dicot weeds compared with the no tackifier treatment, indicating tackifier addition aided dicot suppression. Yield and fruit quality findings were likely indicative of field establishment using weedmat, and further research is needed to ascertain the impact of hydromulches on yield and fruit quality when used at field establishment. Although a few leaf tissue nutrients were slightly outside their ideal ranges, this difference was marginal and occurred across all treatments, indicating that hydromulches maintained bush nutrient status and that differences were due to management and environmental conditions. These combined results illustrate the commercial potential of hydromulches in mature perennial crop systems, especially where dicot weed suppression is the primary concern. Further research is needed to ascertain the economic feasibility of hydromulch technology, its potential impacts on soil health when incorporated into the soil, and long-term impacts on yield, fruit quality, and nutrient status, especially when used at field establishment. Future horticultural research in perennial cropping systems should focus on increasing monocot suppression, decreasing in-field deterioration, and the potential for lowering formulation cost through the addition of agricultural residues.

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