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Reducing Insecticide and Fungicide Loads in Runoff from Plastic Mulch with Vegetative-Covered Furrows

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A common management practice for the production of fresh-market vegetables utilizes polyethylene (plastic) mulch because it increases soil temperature, decreases weed pressure, maintains soil moisture, and minimizes soil contact with the product. However, rain events afford much more erosion and runoff because 50−75% of the field is covered with an impervious surface. A plot study was conducted to compare and to quantify the off-site movement of soil, insecticides, and fungicides associated with runoff from plots planted with Sunbeam tomatoes (*Lycopersicon esculentum* Mill) using the conventional polyethylene mulch management practice vs an alternative management practice—polyethylene mulch-covered beds with cereal rye (*Secale cereale*) planted in the furrows between the beds. The use of cereal rye-covered furrows with the conventional polyethylene system decreased runoff volume by more than 40%, soil erosion by more than 80%, and pesticide loads by 48−74%. Results indicate that vegetative furrows are critical to minimizing the negative aspects of this management practice.

KEYWORDS: Production practices; pesticide; agrochemical; endosulfan; chlorothalonil; esfenvalerate; runoff; soil erosion; plastic mulch; polyethylene mulch; vegetable production; vegetative mulch; insecticide; fungicide

INTRODUCTION

Management and cultivation practices greatly influence the sustainability and environmental impact of agriculture. The transport of agricultural runoff with high sediment levels into adjacent surface waters can affect nontarget organisms adversely as a result of increased turbidity and degraded water quality (*1*−*4*). Runoff has been implicated in the failure of commercial shell fish farms and in contributing to the *Pfiesteria piscicida* outbreaks in the Mid-Atlantic Region of the United States. Runoff has also been shown to contaminate surface waters with pesticides that have harmful effects on aquatic organisms (*5*−*9*). Depending on weather conditions and field slope, as much as 6% of applied pesticides may be transported in runoff from agricultural fields (*10*). Fungicides, bactericides, and insecticides required to protect vegetable crops are known to have adverse effects on shell fish, fin fish, and other aquatic organisms at environmentally relevant levels (*11*−*16*). Pesticides, including those used in vegetable production, have been detected in Chesapeake Bay waterways and other ecosystems (*17*−*22*).

Vegetable producers and growers use polyethylene mulch (typically, a 2 mm sheet of black plastic placed over a raised bed) as the preferred cultivation method for most crops because it controls weeds, warms the soil, and prevents soil from depositing on the crops. In 1996, polyethylene mulch was utilized on an estimated 47.4 km^2 of Virginia's farmland with much of it located on the Delmarva Peninsula (*23*). Tomatoes, a major crop grown in this area, are one of the most economically important vegetables grown in the United States, valued at nearly $2 billion with an annual average yield of 3.5 billion pounds and 9.8 million tons of fresh-market and processing tomatoes, respectively (*24*).

When polyethylene mulch is used, 50−75% of the field is covered with an impervious surface and what soil is not covered with the plastic sheeting (the furrows) is purposely left bare. This practice can cause large amounts of water to run off the fields with an intense pulse of agrochemicals and sediments occurring during rain events. Studies examining the effects of polyethylene mulch use vs no mulch (i.e., bare soil only) revealed that greater runoff volumes were associated with the polyethylene mulch (*15*, *16*, *25*, *26*). This phenomenon was also

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evident in studies comparing plots with impervious polyethylene mulch vs plots completely covered with a vegetative residue mulch (*27*). Although the vegetative mulch covered the entire field, the vegetative residue allowed for greater rainfall infiltration relative to the conventional polyethylene mulch. Thus, greater runoff volumes and soil erosion were observed from the polyethylene mulch plots. In addition, up to 36% of an applied pesticide (copper hydroxide) was recovered in the runoff of polyethylene plots as compared to 6% of the applied copper hydroxide recovered in the runoff of vegetative residue mulch plots (*28*).

Despite the negative environmental aspects of this cultivation method, producers prefer to use polyethylene mulch because of its positive attributes. Thus, alternative management strategies for using polyethylene mulch are needed. Results from the earlier studies strongly suggested that controlling runoff volume and soil losses from the furrows in between the rows of polyethylene mulch-covered beds can avert much of the environmental concerns associated with this cultivation method. The purpose of the current study was to determine if vegetation planted between polyethylene mulch-covered beds would reduce the environmental impact of this desired management practice, allowing the use of the impervious plastic membrane to maintain its positive attributes. Runoff volume and associated pesticide residues and suspended soil particulates were compared from plots of Sunbeam tomatoes (*Lycopersicon esculentum* Mill) grown under two cultivation practices, conventional polyethylene-mulch management (POLY-Bare) and an alternative management practice—polyethylene mulch-covered beds with cereal rye (*Secale cereale*) planted in the furrows between the beds (POLY-Rye).

MATERIALS AND METHODS

Site Description. Runoff water was collected from tomato plots grown using polyethylene mulch on a study site located at the Henry A. Wallace Beltsville Agricultural Research Center (Beltsville, MD). The 2500 m^2 field (5−7% slope) was comprised of Mattapex silt loam (fine-silty, mixed, mesic Aquic Hapludults with 1.3−1.6% organic carbon content) and was divided into 16 plots. A randomized complete block design was used to assign eight plots to tomato production [four plots to polyethylene with bare furrows (Poly-Bare) and four plots polyethylene with cereal rye-covered furrows (Poly-Rye)], and the remaining eight plots were planted with sweet corn (*Zea mays* L). Tomato and corn plots were rotated yearly to reduce pest pressure. Each tomato plot contained four raised beds (15 cm high, 27 m long, 0.9 m wide, with 1.5 m between the centers of two consecutive beds) covered with black polyethylene prepared in a north−south direction.

Cultivation and Plot Management. Tests were conducted prior to the current study to determine which of eight cover crops best withstood typical tractor and foot traffic in furrows between the polyethylene mulch beds (*29*). Cereal rye was chosen because it establishes quickly, provides over 90% groundcover, withstands traffic stresses, and can easily be suppressed by herbicides. Raised beds were constructed, and drip irrigation lines were installed 8−10 cm from the plant row prior to installation of the polyethylene. After the beds were formed, cereal rye was planted in the furrows between the beds of the POLY-Rye plots with a dense seeding rate of 200 kg ha^{-1} that permitted rapid vegetative cover by the time tomatoes were planted. Sunbeam tomato plant (*L. esculentum* Mill) seedlings were transplanted to the center of each bed during mid-May. Urea fertilizer was dissolved in water and applied to the plots through the drip line irrigation system.

Pesticides. Pesticides applied, monitored, and reported in this study were as follows: Bravo 720 fungicide (ISK Biosciences, Mentor, OH) containing 40.4% chlorothalonil (tetrachloroisophthalonitrile); Thiodan 50 WP insecticide (FMC, Philadelphia, PA) containing 50% endosulfan (hexachlorohexahydromethano-2,4,3-benzodioxathiepin 3-oxide); and Asana XL insecticide (DuPont, Wilmington, DE) containing 8.4% esfenvalerate [(s)-cyano(3-phenoxyphenol)methyl(s)-4-chloro-α-(1-methylethyl)benzeneacetate]. Each was applied at recommended rates as a tank mix to the entire plot (raised beds and furrows) resulting in 190 mg/m^2 chlorothalonil, 56 mg/m^2 endosulfan, and/or 3 mg/m^2 esfenvalerate for each application. Physical properties of these active ingredients are given in **Table 1**.

Table 1. Physical Properties of the Applied Pesticides

pesticide	mol wt (g/mol)	solubility (mg/L) (ref)	log K_{ow}^{a} (*41*)
chlorothalonil	265.92	0.6 (*40*)	2.88
endosulfan	406.9	3.7–21^b (*41*, *42*)	3.13
esfenvalerate	419.9	0.0002 (*41*)	4.0

[a] $K_{ow} = C_{octanol}/C_{water}$, where C = molar concentration. [b] Solubility range for α- and β-endosulfan isomers.

Precipitation and Runoff Events. The tomato plots were equipped with a fiberglass H-flume to capture runoff water. Each flume was instrumented with an automated flow meter and sampler (ISCO model 6700, Lincoln, NE). Earthen berms were constructed around each plot to prevent water movement between the plots and to capture runoff only from the three central rows within each four-bed tomato plot. Automated runoff samplers (ISCO 6700) installed at the edge of each plot were equipped with a bubbler flow module (model 730), small microprocessor, compressor, and a differential pressure transducer to measure the water level and were programmed to collect samples on a flow-weighted (volume) basis in 24 300 mL glass bottles. Samples were removed from the field within 12 h following a precipitation event and processed immediately. Runoff samples were thoroughly shaken, and an equal portion from each bottle was composited for analysis and filtered using 0.7 μm GFF filters.

Runoff samples were characterized in terms of total suspended solids and dissolved- and particulate-phase pesticides. Soil loss (kg ha^{-1}) associated with runoff was determined by quantifying the mass of filterable suspended solids per volume of runoff, the total volume of runoff water collected per plot per runoff event, and the size of each plot. Level-to-flow data were recorded every 5 min for as long as the flow module detected water in the flume. A tipping-bucket rain gauge installed next to the field was used to measure the time and intensity of each precipitation event. These data provided sufficient information to determine the time to runoff, time of the total runoff event, total runoff volume, and runoff hydrograph (the profile of the water flux intensity over the course of an event) for each plot.

Dissolved-Phase Pesticides. After filtration, 1 g of NaCl was added to 10 mL of the dissolved phase sample and extracted by shaking with 3 × 5 mL of ethyl acetate. The organic layer was dried with 2.5 g of $MgSO_4$ and was reduced to a final volume of 1 mL under a gentle stream of ultrahigh purity N_2. Extract analyses were carried out with an Agilent (Atlanta, GA) 5890 capillary gas chromatograph (GC) coupled to a 5989A mass spectrometer (MS) operating in negative chemical ionization (NCI) mode. For quality assurance, one blank and one spike recovery sample were extracted with each batch of 10 runoff samples. The blank consisted of a 10 mL portion of organic-free water; a 10 mL portion of organic-free water fortified with target analytes served as the spike recovery solution. No blank sample contained target compounds at levels above instrumental limits of detection (0.005 ppm). All spike recovery values were within acceptable ranges (>90%).

Particle-Phase Pesticides. A quarter of each filter from integrated water samples was extracted with 3:1 dichloromethane (DCM):acetone (chromatographic grade) for 6 h using a Soxhlet apparatus. Extracts were cleaned up using an LC-Alumina-N, 2 g (Supelco, Bellefonte, PA) cartridge topped with 1 g of anhydrous $MgSO_4$. An additional 15 mL of 1:1 DCM:acetone was passed through the clean up column and combined with the extract. Extracts were reduced using a gentle stream of high-purity N_2 gas and exchanged into isooctane. The extraction efficiency of the method was evaluated by spiking filter papers with 2.5−3.0 μg of target analytes as a sample specific extraction efficiency determination. Recoveries ranged from 85 ± 5 to 91 ± 10%. Blank filter papers were also extracted and analyzed with samples, and no

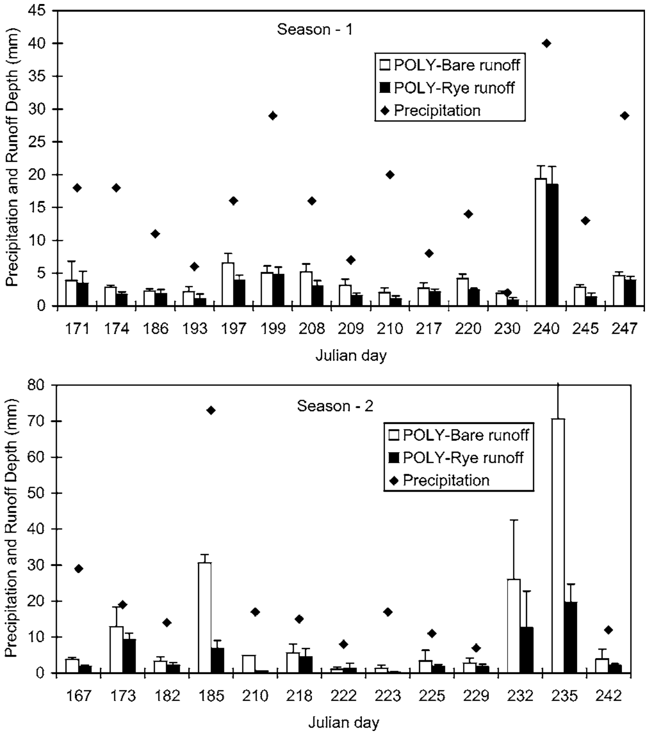

Figure 1. Precipitation and runoff depth per rain event from vegetable production. POLY-Bare, polyethylene-covered vegetable beds and bare soil furrows; POLY-Rye, polyethylene-covered vegetable beds and cereal rye furrows. Error bars represent the standard deviation of the mean.

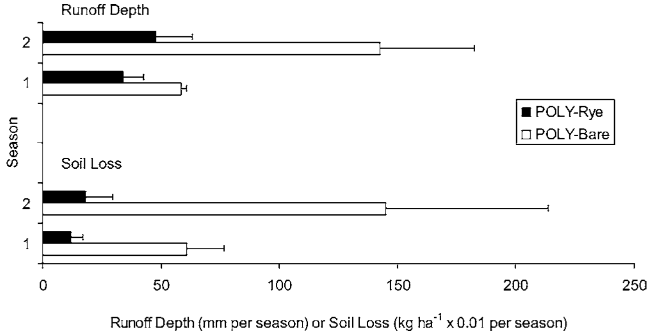

Figure 2. Seasonal runoff depth and seasonal soil loss with runoff from vegetable production. POLY-Bare, polyethylene-covered vegetable beds and bare soil furrows; POLY-Rye, polyethylene-covered vegetable beds and cereal rye furrows. Error bars represent the standard deviation of the mean.

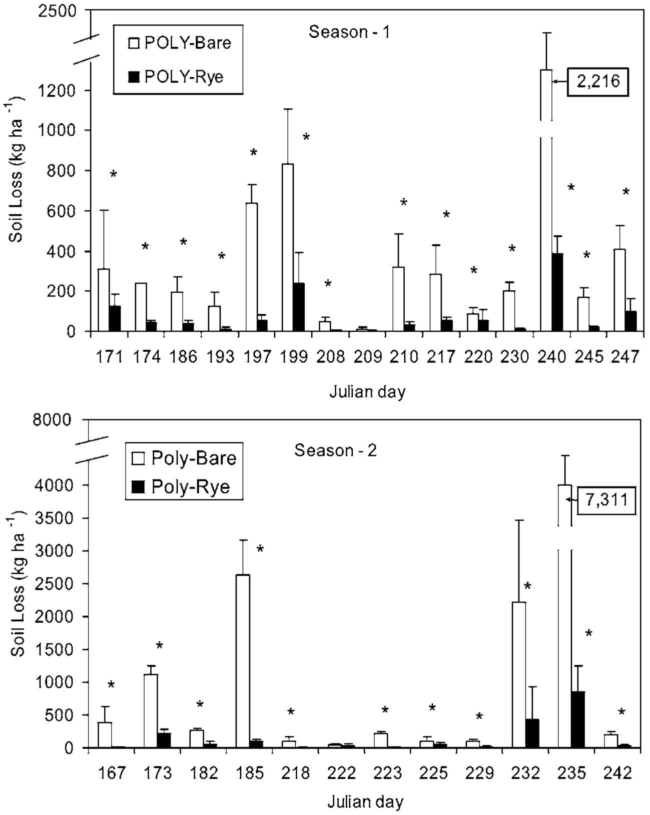

Figure 3. Soil loss per runoff event from vegetable production. POLY-Bare, polyethylene-covered vegetable beds and bare soil furrows; POLY-Rye, polyethylene-covered vegetable beds and cereal rye furrows. Error bars represent the standard deviation of the mean. Asterisks (*) represent a significant difference (p = 0.05) between management practices for the individual runoff events.

interfering peaks were found. Extracts were analyzed using the chromatographic conditions as described above.

Statistical Analysis. Each treatment was assigned to four plots using a randomized complete block design. Analysis of variance determined significant differences in runoff volume, soil loss, and pesticide loading from plots containing tomatoes grown in polyethylene with bare-soil furrows and plots containing tomatoes grown in polyethylene with cereal rye-covered furrows (*30*). The experiment was replicated for two consecutive field seasons (mid-May through early September, 2000 and 2001) with four replications of each treatment per season.

RESULTS AND DISCUSSION

Runoff Volume and Soil Erosion. Runoff volumes from POLY-Bare and POLY-Rye were collected and quantified for 15 and 13 storm events during the first and second growing seasons, respectively. Up to eight times greater runoff volumes were collected from POLY-Bare than from POLY-Rye plots, which ranged from 1.0 to 63.5 and from 0.2 to 17.7 mm for POLY-Bare plots and POLY-Rye plots, respectively (**Figure 1**). In 80% of first season and 62% of second season runoff events, runoff volumes were significantly ($p = 0.05$) less from the POLY-Rye plots than from POLY-Bare plots. Total seasonal water losses were 1.7 and 3 times greater from POLY-Bare plots than POLY-Rye plots in seasons 1 and 2, respectively (**Figure 2**).

Soil losses (kg ha^{-1}) were calculated based on the mass of filterable particulates; losses were not quantified for Julian day 210 in the second season as this was a small event that occurred prior to application of insecticides and fungicides. Soil loss ranged from 10 to 7300 kg ha^{-1} per runoff event (median value, 238 kg ha^{-1} per runoff event) for POLY-Bare plots and from 1 to 850 kg ha^{-1} per runoff event (median value, 42 kg ha^{-1} per runoff event) for POLY-Rye plots (**Figure 3**). The total soil loss from the POLY-Bare plots as compared to the POLY-Rye plots was 5 and 8 times greater for the seasons 1 and 2, respectively (**Figure 2**). This difference in total soil loss between the two cultivation practices was the result of not only the increased runoff volume associated with the POLY-Bare plots but also the greater concentration of suspended particles in the runoff from POLY-Bare plots. The average particulate concentrations in the runoff from bare-soil furrows were 6.4 ± 1.1 mg/mL in season 1 and 8.4 ± 0.5 mg/mL in season 2 as compared to 1.7 ± 1.1 mg/mL in both seasons for runoff from vegetative-covered furrows.

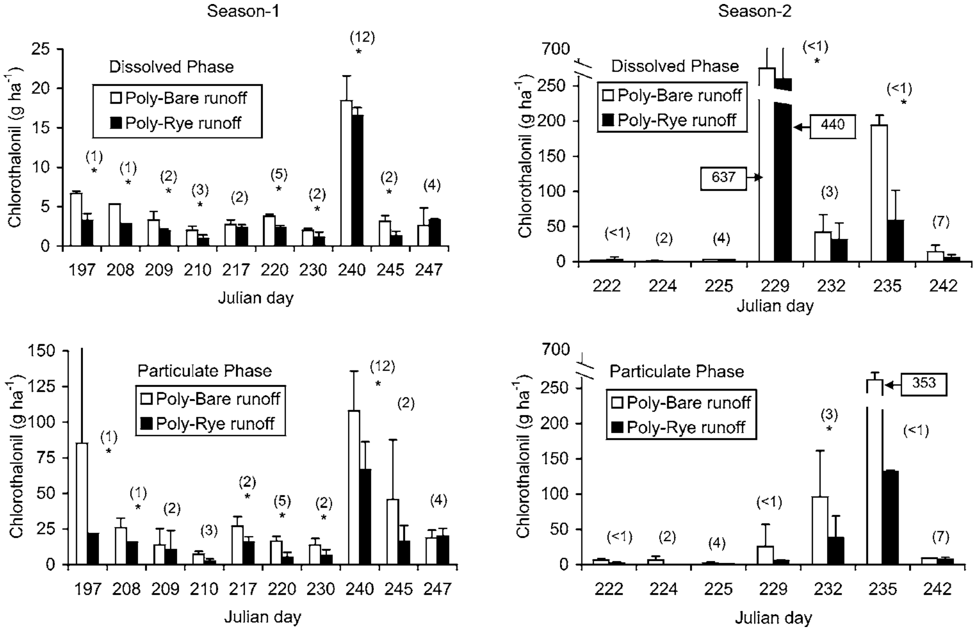

Figure 4. Dissolved-phase and particulate-phase loads of chlorothalonil in runoff per rain event from vegetable production. POLY-Bare, polyethylene-covered vegetable beds and bare soil furrows; POLY-Rye, polyethylene-covered vegetable beds and cereal rye furrows. Error bars represent the standard deviation of the mean. Asterisks (*) represent a significant difference ($p = 0.05$) between management practices for the individual runoff events. Numbers in parentheses represent days between pesticide application and runoff.

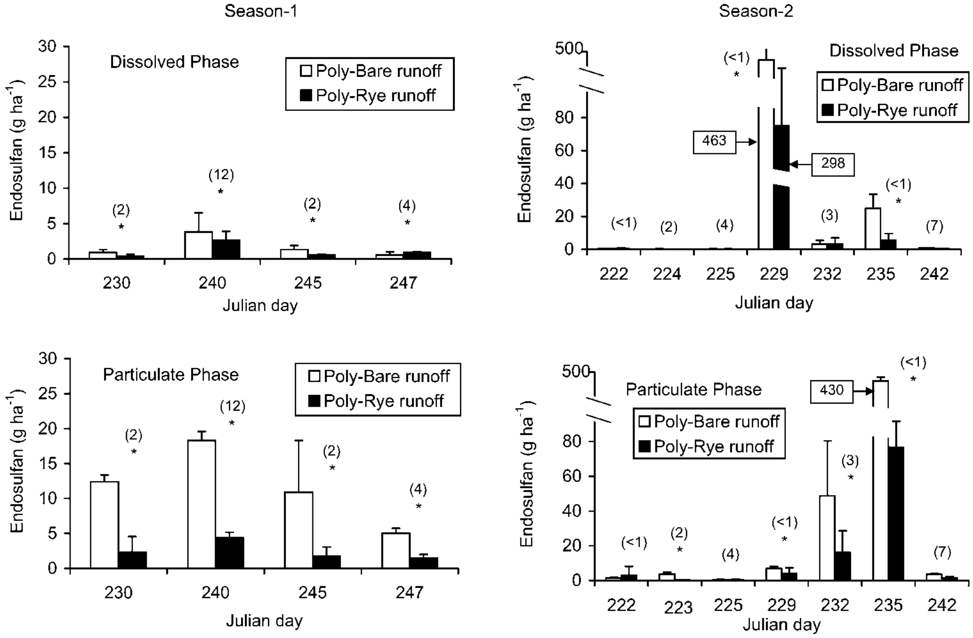

Figure 5. Dissolved-phase and particulate-phase loads of endosulfan in runoff from vegetable production. POLY-Bare, polyethylene-covered vegetable beds and bare soil furrows; POLY-Rye, polyethylene-covered vegetable beds and cereal rye furrows. Error bars represent the standard deviation of the mean. Asterisks (*) represent a significant difference ($p = 0.05$) between management practices for the individual runoff events. Numbers in parentheses represent days between pesticide application and runoff.

The reduction of runoff volume and soil loss observed in the current study can be explained by the increased surface roughness and increased infiltration associated with the vegetative residues. Investigations have shown that crop residues dissipate the energy of raindrops and effectively reduce the velocity and amount of surface runoff (*31*−*34*). Straw mulch was found to reduce runoff and soil loss significantly from agricultural plots (*35*, *36*). In addition, the anchoring characteristics of plant roots and increased structural stability of vegetated soil as compared to nonvegetated soil reduces the availability of soil to be dislodged with runoff water (*37*, *38*).

Pesticide Load as Influenced by Management Practices. Pesticides were applied several times over the growing season. Attempts were made not to apply pesticides if rain was predicted for the day, but in the second season, three precipitation events occurred a few hours after pesticides were applied (Julian days 222, 229, and 235). The event on Julian day 222 occurred over an 8 h period and began as a very gentle rain with a few quick

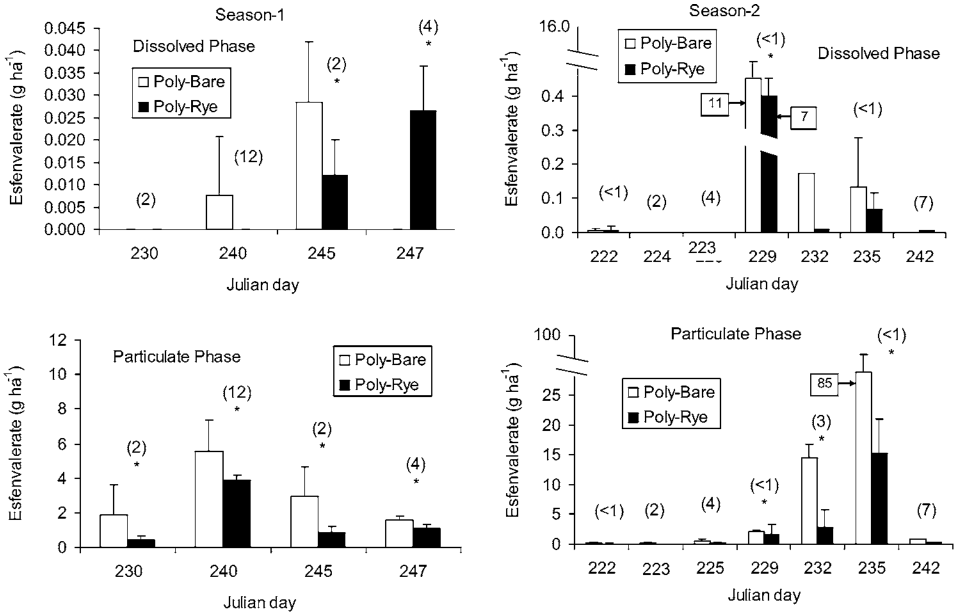

Figure 6. Dissolved-phase and particulate-phase loads of esfenvalerate in runoff per rain event from vegetable production. POLY-Bare, polyethylene-covered vegetable beds and bare soil furrows; POLY-Rye, polyethylene-covered vegetable beds and cereal rye furrows. Error bars represent the standard deviation of the mean. Asterisks (*) represent a significant difference ($p = 0.05$) between management practices for the individual runoff events. Numbers in parentheses represent days between pesticide application and runoff.

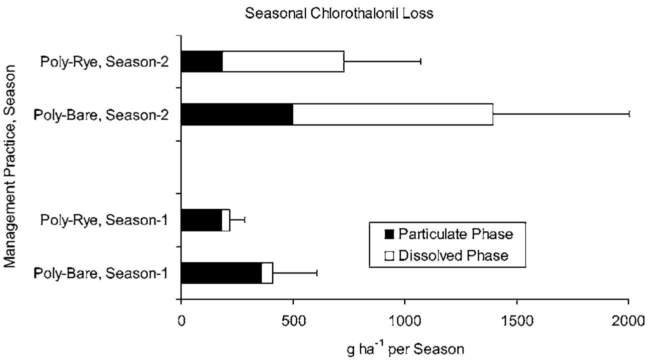

Figure 7. Seasonal loads of chlorothalonil in runoff from vegetable production. POLY-Bare, polyethylene-covered vegetable beds and bare soil furrows; POLY-Rye, polyethylene-covered vegetable beds and cereal rye furrows. Error bars represent the standard deviation of the mean.

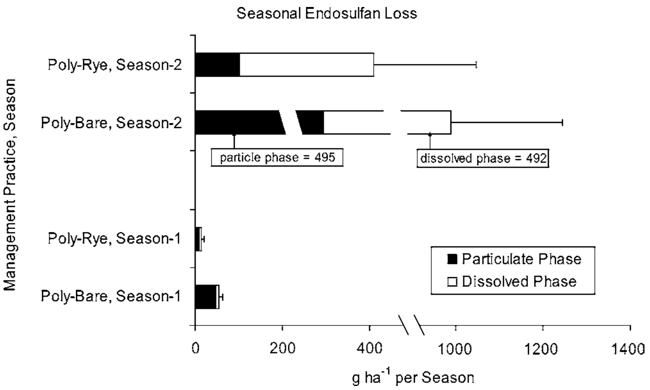

Figure 8. Seasonal loads of endosulfan in runoff from vegetable production. POLY-Bare, polyethylene-covered vegetable beds and bare soil furrows; POLY-Rye, polyethylene-covered vegetable beds and cereal rye furrows. Error bars represent the standard deviation of the mean.

bursts toward the end of the event. On Julian day 229, the precipitation event was short-lived (<1 h) and of moderate intensity, generating some runoff but dislodging only a minimal amount of soil particles. The event of 235 was long-lived (ca. 4 h) and initially very intense, generating an overwhelming amount of runoff and dislodged soil particles particularly in the beginning of the event.

Pesticide loads from both management practices were calculated by determining the amount of pesticide present in the solution phase of the runoff and the amount of pesticide sorbed to the soil particles in the runoff. Overall, the planting of cereal rye in the furrows reduced the dissolved-phase loads in runoff over both seasons by 39% for chlorothalonil, 38% for endosulfan, and 40% for esfenvalerate (chlorothalonil, 944 g ha^{-1} per season Poly-Bare and 576 g ha^{-1} per season Poly-Rye; endosulfan, 500 g ha^{-1} per season Poly-Bare and 312 g ha^{-1} per season Poly-Rye; and esfenvalerate, 11.2 g ha^{-1} per season Poly-Bare and 6.7 g ha^{-1} per season Poly-Rye). This reduction was significant ($p \leq 0.05$) for both chlorothalonil and endosulfan in over half of the individual runoff events (chlorothalonil, 10 of 17 events; endosulfan, 6 of 11 events) but only significant in three of 11 events for esfenvalerate (**Figures 4−6**).

Correlation analysis (r^2) of the initial runoff events following the application of these pesticides revealed that the dissolved-phase loads of these pesticides were attributed more to the quantity of runoff than the concentration of chlorothalonil, endosulfan, and esfenvalerate in the runoff water. This was particularly true for endosulfan and esfenvalerate (chlorothalonil: POLY-Bare, volume $r^2 = 0.99$, concentration $r^2 = 0.77$; chlorothalonil: POLY-Rye, volume $r^2 = 0.98$, concentration $r^2 = 0.72$; endosulfan: POLY-Bare, volume $r^2 = 0.99$, concentration $r^2 = 0.09$; endosulfan: POLY-Rye, volume $r^2 = 0.99$, concentration $r^2 = 0.23$; esfenvalerate: POLY-Bare, volume $r^2 = 0.97$, concentration $r^2 = 0.05$; esfenvalerate: POLY-Rye, volume $r^2 = 0.99$, concentration $r^2 = 0.00$). Julian day 229 of the second season was excluded from the correlation analysis of the dissolved-phase loads as they were 2 orders of magnitude greater than most of the other events and this would skew the results.

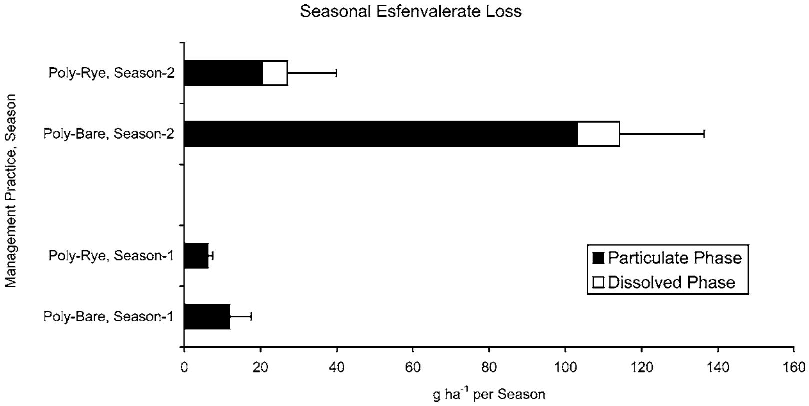

Figure 9. Seasonal loads of esfenvalerate in runoff from vegetable production. POLY-Bare, polyethylene-covered vegetable beds and bare soil furrows; POLY-Rye, polyethylene-covered vegetable beds and cereal rye furrows. Error bars represent the standard deviation of the mean.

Using vegetative-covered furrows vs bare-soil furrows also reduced the particulate-phase loads in runoff over both seasons by 58% for chlorothalonil, by 79% for endosulfan, and by 77% for esfenvalerate (chlorothalonil, 862 g ha^{-1} per season Poly-Bare and 366 g ha^{-1} per season Poly-Rye; endosulfan, 542 g ha^{-1} per season Poly-Bare and 112 g ha^{-1} per season Poly-Rye; and esfenvalerate, 115 g ha^{-1} per season Poly-Bare and 27 g ha^{-1} per season Poly-Rye). The reduction was significant ($p \leq 0.05$) in at least half of the individual runoff events (9 of 17, 8 of 11, and 7 of 11 runoff events for chlorothalonil, endosulfan, and esfenvalerate, respectively) (**Figures 4−6**).

Interestingly, suspended particles from the POLY-Rye plots contained greater concentrations of the pesticides than particulates from POLY-Bare plots. However, correlation analysis of the initial runoff events following the application of chlorothalonil, endosulfan, and esfenvalerate showed that the particulate-phase loads were attributed more to the quantity of soil lost with runoff than the concentration of the pesticide on the particulate especially for the POLY-Rye plots (chlorothalonil: POLY-Bare, $r^2 = 0.15$ soil loss, $r^2 = 0.10$ concentration; chlorothalonil: POLY-Rye, $r^2 = 0.64$ soil loss, $r^2 = 0.05$ concentration; endosulfan: POLY-Bare, $r^2 = 0.27$ soil loss, $r^2 = 0.00$ concentration; endosulfan: POLY-Rye, $r^2 = 0.96$ soil loss, $r^2 = 0.12$ concentration; esfenvalerate: POLY-Bare, $r^2 = 0.25$ soil loss, $r^2 = 0.05$ concentration; and esfenvalerate: POLY-Rye, $r^2 = 0.95$ soil loss, $r^2 = 0.40$ concentration).

Pesticide Loads as Influenced by Phase Distribution. As is common practice, the fungicide (chlorothalonil) and insecticides (endosulfan, esfenvalerate) in this study were applied directly to the tomato plants. Inevitably, a portion of these compounds is inadvertently applied to the underlying mulch during foliar application. The residues can also be transferred from the plant to the mulch as a result of foliar wash off with precipitation. The quantity and phase distribution of these losses are influenced by the physical and chemical properties of the pesticide; the interaction of the pesticide with soil, plastic, and plant tissue; the availability of the pesticide to be transported with runoff via the dissolved phase or sorbed to suspended particles; and ultimately, the timing of application and the intensity and duration of the precipitation events.

Total seasonal loads of pesticides in the dissolved- and particle-phases of the runoff were compared to determine the overall effects of management practice and to consider which fraction contributed the most to the total pesticide load (**Figures 7−9**). In general and irrespective of management practice during the first season, greater loads of all three pesticides were measured in the particle-phase than the dissolved-phase (percentage load from particle phase: POLY-Bare: chlorothalonil, 88%; endosulfan, 88%; and esfenvalerate, >99%; POLY-Rye: chlorothalonil, 83%; endosulfan, 68%; and esfenvalerate, >99%). In the second season, three rain events occurred within 24 h of application on Julian days 222, 229, and 235 (**Figures 4−6**). Thus, total quantities of all three pesticides measured in runoff during the second season were much greater than those reported in runoff during the first season. Furthermore, this also affected the phase distribution; for chlorothalonil and endosulfan, the dissolved phase contributed more to the overall load than the particulate phase (percentage load from particle phase: POLY-Bare: chlorothalonil, 36%; endosulfan, 50%; POLY-Rye: chlorothalonil, 26%; endosulfan, 25%). Greater loads from the particle phase were observed in both management practices for esfenvalerate (POLY-Bare, 91%; POLY-Rye, 80%) due to its hydrophobicity (solubility = 0.0002 mg/L). In all cases, greater particle-phase loads were observed from the Poly-Bare than Poly-Rye.

Effects and Environmental Impacts of Management Practices. Although applying pesticides just prior to a rain event is not usually recommended, sudden summer thunderstorms along the East Coast of the United States frequently occur. Implementation of vegetative-covered furrows to conventional polyethylene mulch systems reduced runoff volume by more than 40%, thereby adding some protection from unexpected storm events. In addition, soil erosion was reduced by 80% and overall pesticide loads from 48 to 74%. The results of this study clearly show that when using polyethylene mulch for its positive attributes (increasing soil temperature, decreasing weed pressure, and maintaining soil moisture), vegetative furrows are critical to minimizing the negative aspects of this management practice. Vegetative furrows essentially function as in-field buffers; they reduce soil erosion, retaining valuable top soil in the field; increase pesticide efficacy by maintaining plant protection products at their intended site of application; and reduce off-site chemical transport and the associated negative environmental impacts. These infield buffers do not reduce harvest yields as previously reported (*39*) nor do they require additional production acreage as is often the case with edge-of-field buffers. Furthermore, the cereal rye senesces early in the tomato growing season and does not compete for nutrients or water; thus, no additional irrigation or fertilizers are required. Overall, this research shows that adoption of this alternative management practice provides growers with desired outcomes while significantly reducing adverse environmental impacts associated with conventional vegetable production.

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