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USE OF VEGETATIVE FURROWS TO MITIGATE COPPER LOADS AND SOIL LOSS IN RUNOFF FROM POLYETHYLENE (PLASTIC) MULCH VEGETABLE PRODUCTION SYSTEMS

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Abstract—The transport of runoff with high copper concentrations and sediment loads into adjacent surface waters can have adverse effects on nontarget organisms as a result of increased turbidity and degraded water quality. Runoff from vegetable production utilizing polyethylene mulch can contain up to 35% of applied copper, a widely used fungicide/bactericide that has adverse effects on aquatic organisms. Copper is primarily transported in runoff with suspended particulates; therefore, implementation of management practices that minimize soil erosion will reduce copper loads. Replacing bare-soil furrows with furrows planted in rye (*Secale cereale*) significantly improved the sustainability of vegetable production with polyethylene mulch and reduced the potential environmental impact of this management practice. Vegetative furrows decreased runoff volume by >40% and soil erosion by >80%. Copper loads with runoff were reduced by 72% in 2001, primarily as a result of reduced soil erosion since more than 88% of the total copper loads were transported in runoff with suspended soil particulates. Tomato yields in both years were similar between the polyethylene mulch plots containing either bare-soil or vegetative furrows. Replacing bare-soil furrows with vegetative furrows greatly reduces the effects of sediments and agrochemicals on sensitive ecosystems while maintaining crop yields.

Keywords—Copper Runoff Soil erosion Polyethylene mulch Vegetative furrows

INTRODUCTION

Cultivation and management practices greatly influence the sustainability and environmental impact of agriculture. Polyethylene mulch is widely accepted and utilized in the production of vegetables and other row crops to control weeds, warm the soil, and prevent soil from depositing on the crops. In 1996, polyethylene mulch was used on an estimated 47.4 km^2 of farmland in the state of Virginia, USA, with 36.8 km^2 located on Virginia's Eastern Shore [1]. Management practices involving polyethylene mulch have been reported to significantly increase soil erosion and the quantity of agrochemicals that are lost with runoff [2,3].

The National Agricultural Pesticide Impact Assessment Program reported that copper was applied to 90% of the fresh-market tomatoes grown in Virginia in 1993, involving 10 applications throughout the growing season and resulting in a seasonal application of 13,157 kg of copper hydroxide [4]. Typically 1 to 6% of applied agrochemicals are removed from agricultural areas with surface runoff [5]. Management practices utilizing polyethylene mulch have been shown to increase copper loading with runoff to as much as 36% of the applied agrochemical [2].

Copper hydroxide, a widely used fungicide-bactericide often applied prophylactically for control of vegetable diseases, is reasonably soluble in water and potentially bioavailable. Copper has two oxidation states, Cu^{+} (cuprous) and Cu^{2+} (cupric), and is present in both soluble and particulate forms in the environment [6,7]. The chemical form of copper is important to its bioavailability, behavior in biological processes, and toxicity to aquatic organisms. In aerated water with a pH range of most natural waters (6–8), cuprous copper is unstable and will oxidize to the cupric form, which is the predominant oxidation state in soluble aqueous complexes and considered the most environmentally relevant and toxic form to aquatic life [6–8]. Cupric ions can adsorb to sediments, clays, and organic particulates and form complexes with organic or inorganic compounds [9,10]. Copper has been shown to be primarily transported in runoff with suspended particulates [2] and desorbed as soluble copper when copper-adsorbed particulates in freshwater come in contact with seawater in estuarine environments [11,12]. The use of polyethylene mulch, along with the large application of copper hydroxide, increases the potential off-site transport of copper with runoff and the exposure of sensitive aquatic ecosystems to a compound that has been shown to have adverse effects [13–15]. Although research has shown that cultivation practices utilizing polyethylene mulch are less sustainable and have greater adverse effects on the environment, vegetable producers prefer polyethylene mulch and are reluctant to abandon this cultivation system because of its ability to warm the soil and accelerate initial tomato harvest. Because runoff from vegetable production with polyethylene mulch has been shown to contribute to elevated copper concentrations in neighboring surface waters at

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levels that are toxic to aquatic organisms [12], a need exists to modify the current polyethylene mulch vegetable production system so as to increase its sustainability and minimize its environmental impact.

The overall objective of this project was to evaluate the use of vegetative furrows to reduce the environmental impact of vegetable production with polyethylene mulch. Specifically, runoff volume, copper loads, and soil loss with runoff were quantified and compared between the conventional polyethylene mulch/bare soil furrow (BSF) system and a modified polyethylene mulch/cereal rye (*Secale cereale*) furrow (CRF) system. In addition, runoff water was analyzed to determine the distribution of copper in the dissolved and particulate phases of runoff. Results from previous studies indicate that controlling soil loss will decrease copper losses and should decrease toxicity of runoff to the surrounding ecosystems [2,12]. One way to control soil loss is to cover bare soil with a vegetative cover crop. In a preliminary study, eight cover crops were tested in furrows between polyethylene-covered beds to determine which could withstand typical tractor and foot traffic [16]. Cereal rye was chosen because it establishes quickly, provides >90% groundcover, withstands traffic stresses, and can be suppressed easily by herbicides.

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, USA). This site was chosen for its slope (5–7%) to facilitate the collection of runoff water. The 2,500-m^2 field (Mattapex silt loam: fine-silty, mixed, mesic Aquic Hapludults with 1.3–1.6% organic carbon content) was divided into 16 plots. In 2000, a randomized complete block design was used to assign eight plots to tomato production (four plots to each of the two furrow treatments) and the remaining eight plots to corn. Tomato and corn plots were rotated in 2001 to reduce pest pressure.

Each tomato plot contained four raised beds (15 cm high, 27 m long, 0.9 m wide, and 1.5 m center-to-center) covered with black polyethylene, prepared in a north–south direction. The tomato plots were equipped with a fiberglass H-flume to capture runoff water. Each flume was instrumented with an automated flow meter and runoff sampler containing 24, 350-ml glass bottles (ISCO model 6700, Lincoln, NE, USA). Earthen berms were constructed around each plot to prevent water movement between the plots. Runoff was collected from the three central rows within each four-bed tomato plot.

Management practices

Four tomato plots were assigned to each of the following treatments: Tomatoes grown on raised polyethylene-covered beds with bare soil furrows between the beds or tomatoes grown on raised polyethylene-covered beds with cereal rye planted in the furrows. The polyethylene-covered beds were formed in late April, and cereal rye was planted in the furrows of the CRF plots. During mid-May, Sunbeam tomato plant seedlings were transplanted to the center of each bed. Measured trickle irrigation lines under the polyethylene maintained the plants during dry conditions. Urea fertilizer was dissolved in water and applied to the plots through this irrigation system. Pesticides monitored in the experiment were Lexone-7 herbicide (Du Pont, Wilmington, DE, USA) containing 75% metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5 (4*H*)-one], Asana7 XL insecticide (Du Pont) containing 8.4% esfenvalerate [(s)-cyano(3-phenoxyphenol)methyl(s)-4-chloro-α-(1-methylethyl) benzeneacetate], Thiodan7 50 WP insecticide (FMC, Philadelphia, PA, USA) containing 50% endosulfan (hexachlorohexahydromethano-2,4,3-benzodioxathiepin 3-oxide), Bravo7 720 fungicide (ISK Biosciences, Mentor, OH, USA) containing 40.4% chlorothalonil (tetrachloroisophthalonitrile), and Kocide7 101 fungicide/bactericide (Rhône Poulenc, France) containing 77% copper hydroxide. Each was applied at recommended rates, which resulted in the application of 42 mg/m^2 metribuzin, 3 mg/m^2 esfenvalerate, 56 mg/m^2 endosulfan, 190 mg/m^2 chlorothalonil, 129 mg/m^2 copper, or a combination of treatments for each application.

Rye was planted in furrows of the CRF plots with a dense seeding rate of 200 kg/ha that permitted rapid vegetative cover by the time tomatoes were planted. Rye was subsequently suppressed by tractor tire traffic associated with planting, by foliar herbicide applications to the furrow, and by hot summer temperatures. At midseason, furrows in the CRF treatment were covered by a combination of dead residue and vegetation not exceeding 30 cm high.

Precipitation events and runoff collection

The ISCO automated samplers were equipped with an ISCO bubbler flow module (model 730) that contains a small microprocessor, a compressor, and a differential pressure transducer to measure the water level in the H-flume. The ISCO 6700 controller uses the known level-to-flow relationship of the H-flume to calculate the flow rate and total flow from the level measurement. Level-to-flow data was recorded every 5 min for as long as the flow module detected water in the flume. A tipping-bucket rain gage measured the time and intensity of each rain event. The level-to-flow data from each plot and the field rain gage 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, as well as the total rainfall. The automated samplers were programmed to collect samples on a flow-weighted (volume) basis. The date and time were recorded as the peristaltic pump and distributor arm delivered 300 ml of runoff to each sample bottle. A total of 24, 300-ml samples can be collected from each event. Collection of flow rate and runoff volume data continued until the end of the runoff event. Water samples were removed from the samplers following the rain event, placed on ice, and transported to the laboratory for immediate processing.

Runoff extraction and analysis

Individual and integrated water samples were characterized for total suspended solids and for total copper or dissolved- and particulate-phase copper. Copper concentrations were determined following the methods of Lindsay and Norvell [17] and the American Public Health Association [18]. A detailed description of the sample processing and extraction and analysis methods are given elsewhere [2,3]. A brief description of copper extraction and analysis is presented here along with slight changes in the sample preparation method.

Immediately following field collection and sample integration, 100 ml of the integrated runoff samples were filtered through a preweighed, 0.2-μm pore size Nuclepore-Track-Etch membrane filter (Whatman, Clifton, NJ, USA) to separate the dissolved and particulate phases. Dissolved phase portions were preserved with 3 ml of 16 N nitric acid and stored at room temperature until digestion. Membrane filters containing the particle phase were air dried, weighed, and stored until analysis.

Dissolved-phase copper was extracted using nitric acid (HNO_3) and hydrochloric acid (HCl) digestion in acid-washed glassware [18]. Analyses were carried out with a Varian SpectrAA 300/400 atomic absorption spectrophotometer (Walnut Creek, CA, USA; wavelength, 324.8 nm; flame, air acetylene). Unfiltered runoff water was processed for total copper following the same HNO_3/HCl digestion process. Deionized water blank samples were processed with field samples as controls and no contamination was observed above the minimum detection limit of 0.03 μg/ml. Collection efficiency of the digestion process was assessed by including deionized water samples spiked with copper hydroxide (160 μg/L) with each batch of field runoff samples. Copper recoveries from the dissolved phase averaged 98 ± 3% (n = 15).

Particulate-phase copper concentrations were determined by extracting particulates, captured on the membrane filters, with a diethylenetriaminepentaacetic acid (DTPA) solution following methods modified from Lindsay and Norvell [17]. Particulate extracts were analyzed by atomic absorption spectrometry as previously described. Blank matrix samples were spiked with 8 μg of copper hydroxide and extracted to determine the extraction efficiency. Recoveries of copper from spiked samples averaged 99 ± 4% (n = 15). Additional blank soil samples were processed with field samples as controls, and no contamination was observed above the detection limit of 0.03 ± 0.01 μg/ml.

Statistical analysis

Furrow treatment, BSF or CRF, was the single criteria of classification for the data. Analyses of variance (ANOVA) were performed comparing runoff collected during each of the field seasons. A significant F (at 0.01 or 0.05) implied a real difference among treatment means. The least significant difference (LSD) determined statistical significance between treatment means for each runoff event (LSD, 0.05 = error df and 0.05 probability to determine two-tailed t values) [19]. These analyses were performed to determine statistical differences between furrow treatments for runoff volume, concentration of suspended particulates, soil loss, copper concentration on the particulates, dissolved copper concentrations, and copper loading for each runoff event. Geometric means (±SD) were calculated to provide a single value for the comparison of overall seasonal trends between the two management practices [20]. Geometric means were used rather than the arithmetic means because one or several runoff events within a growing season were one or two order(s) of magnitude greater than the other runoff events. Correlation analyses were performed comparing copper loads with runoff volume, dissolved copper concentrations, particulate copper concentrations, and copper concentrations on the particulates to determine which of these factors had the greatest effect on dissolved- or particulate-phase copper loading.

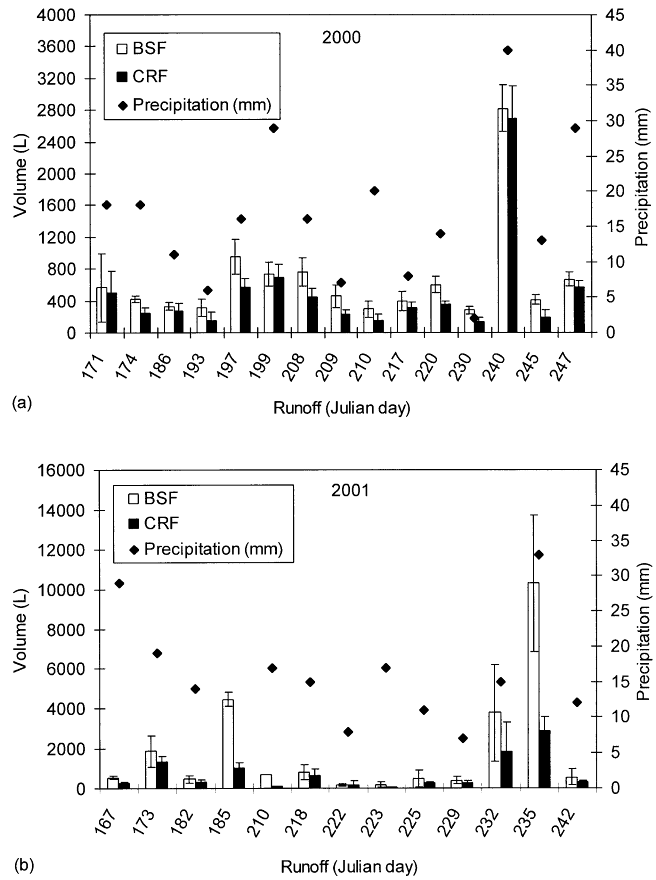

Fig. 1. Precipitation and runoff volume from polyethylene mulch/bare soil furrow (BSF) plots and polyethylene mulch/cereal rye furrow (CRF) plots during the 2000 (**a**) and 2001 (**b**) growing seasons. Error bars represent the standard deviation of the means. The difference in runoff volume between plot treatments was significant (LSD, 0.05) for all runoff events with the exception of Julian days 171, 186, and 199 of 2000 and Julian days 182, 218, 222, 223, and 229 of 2001.

RESULTS AND DISCUSSION

Runoff volume

Runoff volume was collected and quantified for 15 and 13 storm events during the 2000 and 2001 growing seasons, respectively. Significantly larger volumes (LSD, 0.05) of runoff were collected from the BSF plots for 80% of the runoff events in 2000 (Fig. 1a) and 62% of the runoff events in 2001 (Fig. 1b). Runoff volumes from plots with bare-soil furrows were up to eight times greater than the runoff volumes from the plots with vegetative furrows for individual storm events. Seasonal water losses were 1.7 and 3.0 times greater from BSF plots (58 ± 2 and 143 ± 40 L/m²/growing season) than from CRF plots (34 ± 11 and 48 ± 16 L/m²/growing season). The practice of covering raised tomato-beds with polyethylene mulch greatly reduces rainfall infiltration because 50 to 75% of the field might be covered with an impermeable surface. The reduction of runoff water volume could be a result of reduced soil moisture and consequently increased water demand. Additionally, rye crop residues dissipate the energy of raindrops and effectively reduce the velocity and amount of surface runoff [21,22]. Surface runoff can be a carrier for both soil particles and dissolved and particulate-bound agrochemicals. Therefore, implementation or alteration of management practices that reduce runoff volume should lessen soil erosion and the off-site transport of agrochemicals to surrounding areas.

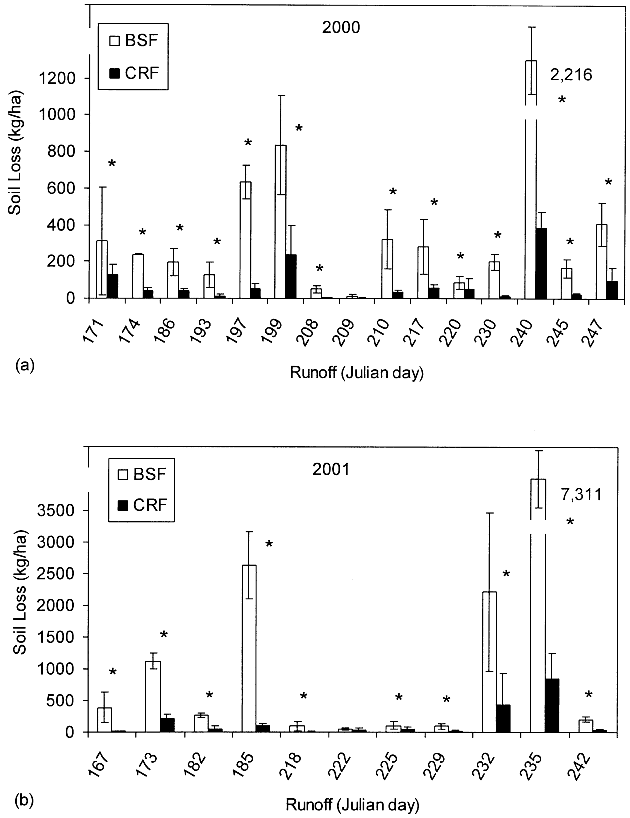

Fig. 2. Quantity of soil lost with runoff from polyethylene mulch/bare soil furrow (BSF) plots and polyethylene mulch/cereal rye furrow (CRF) plots during the 2000 (**a**) and 2001 (**b**) growing seasons. An asterisk (*) represents a significant difference (LSD, 0.05) in soil loss between plot treatments. Error bars represent standard deviation of the means.

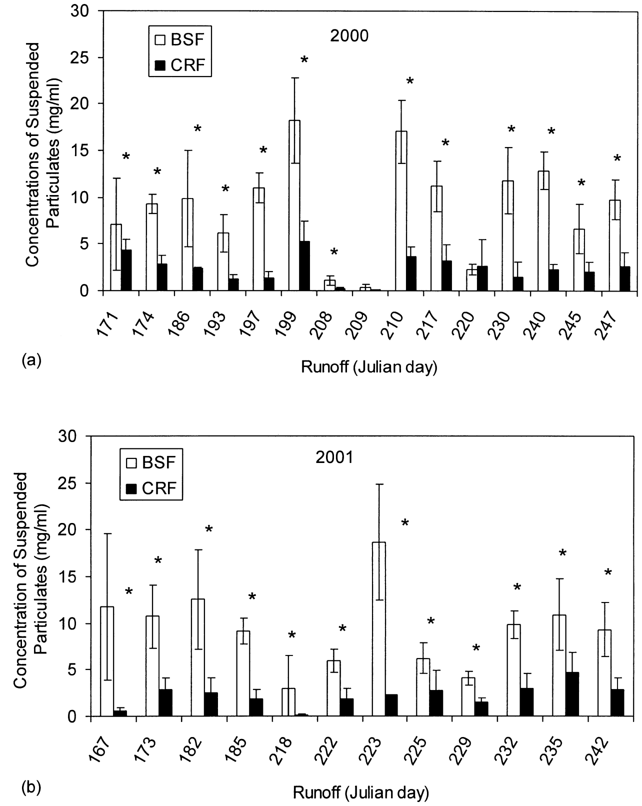

Fig. 3. Concentration of suspended particulates measured in runoff from polyethylene mulch/bare soil furrow (BSF) plots and polyethylene mulch/cereal rye furrow (CRF) plots during the 2000 (**a**) and 2001 (**b**) growing seasons. An asterisk (*) represents a significant difference (LSD, 0.05) in runoff particulate concentrations between plot treatments. Error bars represent standard deviation of the means.

Soil erosion

Soil loss (kg/ha) was calculated on the basis of the mass of filterable particulates/volume of runoff, the total volume of runoff water collected/plot/runoff event, and the size of each plot. Vegetative furrows significantly reduced (LSD, 0.05) the amount of soil loss loads in runoff in 94 and 90% of the runoff events in 2000 and 2001, respectively. Soil loss ranged from 10 to 7,300 kg/ha/runoff event for BSF treatments compared to 1 to 850 kg/ha/runoff event for CRF treatments in the 2000 and 2001 seasons (Fig. 2a and b). The load of soil measured in individual runoff events from the BSF plots was 2 to 44 times greater than the amount measured in the runoff from the CRF plots. The average soil loss for individual runoff events in the 2000 and 2001 growing seasons was six times greater from the BSF plots than from the CRF plots (217 ± 1.25 and 410 ± 1.62 kg/ha/runoff event for BSF plots; 35.6 ± 1.47 and 58.5 ± 1.52 kg/ha/runoff event for CRF plots). The difference in soil loss between the two mulch systems was the result of both the increased runoff volume (Fig. 1a and b) and greater concentration of suspended sediments associated with the BSF plots (Fig. 3a and b). Runoff from BSF plots contained up to 24 times the concentration of suspended solids compared with runoff from CRF plots. The average particulate concentrations for BSF plots were four and five times greater than those from CRF plots (6.44 ± 1.09 mg/ml [2000] and 8.39 ± 0.51 mg/ml [2001] for BSF plots; 1.69 ± 1.13 mg/ml [2000] and 1.70 ± 0.98 mg/ml [2001] for CRF plots).

Greater runoff volumes increase the opportunity for off-site transport of soil with runoff. In addition, flow rate of runoff can influence the quantity of particulates that can be suspended and carried with runoff. The anchoring characteristics of plant roots and increased structural stability of vegetated soil compared to nonvegetated soil reduces the availability of soil to be dislodged with runoff water. In addition, the presence of the cereal rye residue reduced the velocity of the runoff flow by 1.3 to 2.4 times that of the BSF treatments. Research has shown crop residues dissipate the energy of raindrops and effectively reduce the velocity and amount of surface runoff [21,22]. Straw mulch was observed to reduce runoff and soil loss significantly from agricultural plots [23,24]. The significant reduction in soil loading with the rye vegetative furrows relative to bare-soil furrows is believed to result from a combination of several factors, including the increased soil stability with plant roots and the reduced runoff volume and flow rate measured in the plots with vegetative furrows.

Copper

Unfiltered runoff: Total copper. Equal quantities of individual runoff subsamples collected from each plot were combined into eight samples, one integrated sample/plot for each runoff event, and analyzed to compare copper loads from the bare-soil and vegetative furrow plots during the 2000 growing season (Fig. 4a). Significantly greater loads (LSD, 0.05) of copper were measured in unfiltered runoff from BSF plots (80–442 g/ha/runoff event) than from CRF plots (30–176 g/ha/runoff event) for all runoff events following the application of Kocide. Average copper loads were almost three times

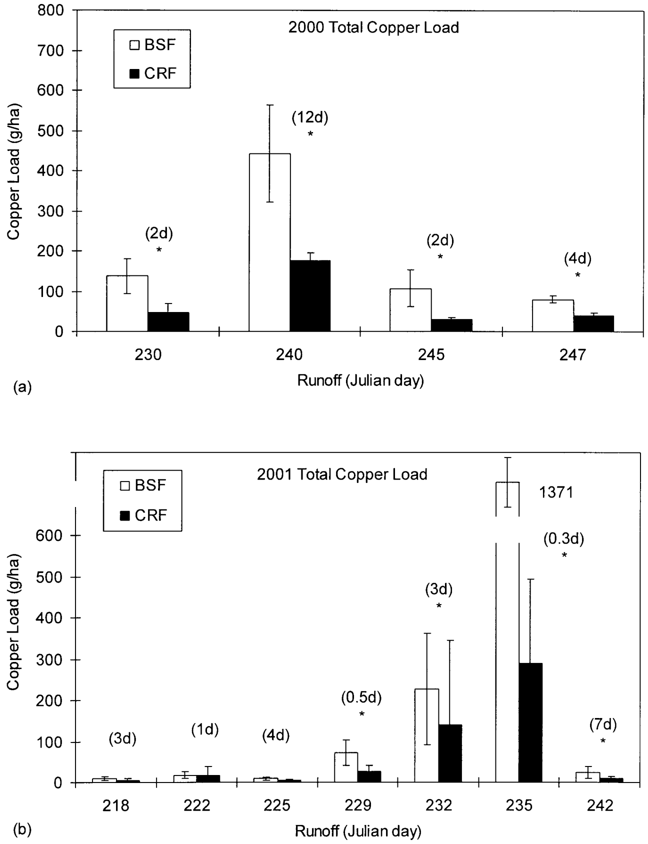

Fig. 4. Total copper loads in 2000 (**a**) and 2001 (**b**) runoff from polyethylene mulch/bare soil furrow (BSF) plots and polyethylene mulch/cereal rye furrow (CRF) plots after the application of copper hydroxide (active ingredient of copper, 0.169 g copper/m^2 plot · four applications). Numbers in parentheses represent days between copper hydroxide application and runoff. An asterisk (*) represents a significant difference (LSD, 0.05) in the copper load between plot treatments for the individual runoff event. Error bars represent standard deviation of the means.

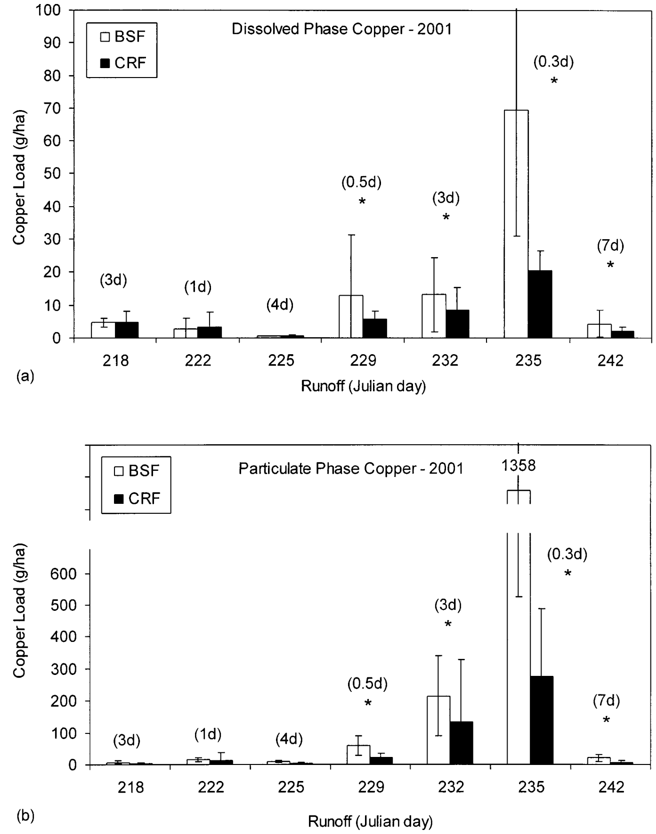

Fig. 5. Dissolved-phase (**a**) and particulate-phase (**b**) loads of copper in the 2001 runoff from polyethylene mulch/bare soil furrow (BSF) plots and polyethylene mulch/cereal rye furrow (CRF) plots after the application of copper hydroxide (active ingredient of copper, 0.169 g copper/m^2 plot · four applications). Numbers in parentheses represent days between copper hydroxide application and runoff. An asterisk (*) represents a significant difference (LSD, 0.05) in the copper load between plot treatments for the individual runoff event. Error bars represent standard deviation of the means.

greater from BSF plots (151 ± 0.8 g/ha/runoff event) relative to loads from CRF plots (56 ± 0.8 g/ha/runoff event). At the completion of the growing season, 19.8% of the copper applied to the BSF plots had been removed from the field through runoff. Planting cereal rye in between the polyethylene-covered beds reduced total copper loading, with runoff to 7.6% of the applied copper for the CRF plots. Total copper loads for the 2001 season (the sum of dissolved- and particulate-phase loads presented in the following sections) were also significantly reduced (LSD, 0.05) in the runoff of the CRF plots relative to the BSF plots (Fig. 4b). Copper loads ranged from 8.8 to 1,371 g/ha/runoff event for BSF treatments and 4.0 to 283 g/ha/runoff event for CRF treatments. The geometric mean for the total copper load in runoff from BSF plots was 2.5 times greater than runoff from CRF plots (60 ± 1.8 g/ha/runoff event for BSF treatments; 24 ± 1.6 g/ha/runoff event for CRF treatments).

Dissolved-phase copper. Runoff from BSF plots contained significantly greater (LSD, 0.05) loads of copper in the operationally defined dissolved-phase runoff for half of the runoff events following the application of Kocide (Fig. 5a). Individual runoff loads ranged from 0.4 to 70 g/ha for BSF plots and 0.2 to 20 g/ha for CRF plots (geometric mean ± SD = 4.4 ± 1.7 g/ha for BSF plots and 2.8 ± 1.5 g/ha for CRF plots). The seasonal load of copper measured in the dissolved phase of the runoff was 2.4 times greater in BSF plots than in CRF plots, which represented 2.1% and 0.9% of the applied copper, respectively. Dissolved-phase copper concentrations were comparable in all of the evaluated runoff events. Therefore, the greater dissolved-phase loads of copper from plots with bare-soil furrows were the result of the increased runoff volume rather than a difference in dissolved-phase copper concentrations (correlation analysis—BSF: volume $r = 0.93$, copper concentration $r = 0.002$; CRF: volume $r = 0.84$, copper concentration $r = 0.03$).

Particulate-phase copper. Runoff collected from BSF plots contained two to five times greater loads of particulate-phase copper than runoff from CRF plots (7.6–1,358 g/ha/runoff event for BSF plots; 3.3–275 g/ha/runoff event for CRF plots) (Fig. 5b). The geometric mean of individual particulate-phase copper loads was more than two times greater for plots with bare-soil furrows than plots with vegetative furrows (44.3 ± 1.91 g/ha/runoff event for BSF; 19.1 ± 1.71 g/ha/runoff event for CRF). Suspended particles from the CRF plots contained greater concentrations of copper than particulates from BSF plots. The geometric mean of individual particulate-phase copper concentrations was two times greater for plots with vegetative furrows (167 ± 0.8 μg/g/runoff event for BSF; 355 ± 0.9 μg/g/runoff event for CRF). Correlation analysis (r) of runoff events following the application of copper hydroxide showed that particulate-phase loads of copper were attributed more to the quantity of soil lost with runoff than the concentration (BSF: soil loss $r = 0.98$, copper concentration $r = 0.002$; CRF: soil loss $r = 0.99$, copper concentration $r = 0.06$). This would explain the greater particulate-phase copper load from the BSF plots despite the greater concentration of copper associated with particulates in runoff from the CRF plots. The copper load in the particulate-phase of runoff was 32.6% and 8.8% of the copper applied during the 2001 growing season for BSF and CRF plots, respectively.

Phase distribution in relation to total copper load. Dissolved- and particulate-phase copper loads measured in the 2001 runoff were compared to determine which phase contributed more to the total copper load. Significantly greater loads (LSD, 0.05) of copper were measured in the particulate phase than in the dissolved phase of runoff from both the BSF and CRF plots, with the particulate phase accounting for 93 ± 6.5% and 88 ± 11% of the copper loads, respectively (Fig. 5a and b). This is similar to the distribution of copper loads observed in a previous study with polyethylene and hairy vetch mulch [2].

Environmental fate and toxicological concerns. The interaction of pesticides with polyethylene mulch and soil and their availability for transport with runoff are dependent on the physical and chemical properties of the pesticide. Copper hydroxide is applied to the tomato plants for disease control; however, a percentage of this fungicide is either washed off the foliage onto the polyethylene mulch or unintentionally applied to the mulch during foliar application. On the basis of the water solubility of copper hydroxide (2.9 mg/L at pH 7, 25°C) [25] and our observations from a previous study [2], copper appears to be readily washed off polyethylene mulch and transported in surface runoff long after application (>30 d postapplication). Eighty-eight percent and 93% of the copper loads were associated with the particulate phase of the runoff. This could be the result of sorption of cupric copper to sediments, clay, and particulates transported with the runoff [6,7]. The concentration of copper extracted from the particulates was greater from the CRF plots than the BSF plots. Meador et al. [26] reported that microcosm-derived organic carbon and ligands produced by algal species are able to complex copper. It is possible that the greater concentration of copper observed with the particulates from the CRF plots could be the result of the formation of complexes between copper and organic compounds resulting from the degradation of the cereal rye. Despite the greater concentrations of copper adsorbed or complexed with particulates in the CRF runoff, total copper loads from the CRF plots were less than those observed in the BSF runoff as a result of reduced quantities of particulates. Particulate-phase copper has been shown to desorb as soluble copper in both seawater and freshwater, therefore becoming more bioavailable [11,12]. Aquatic biota can bioconcentrate copper in their tissue (bioconcentration factors: 2,000 for freshwater algae, 28,200 for saltwater bivalves) [7] and be acutely toxic to aquatic species at low levels (1.3 μg/L for *Daphnia* tested in freshwater, 1.2 μg/L for a bivalve tested in saltwater) [27–29]. Copper has been shown to adversely affect fish, causing histological alterations in chemoreceptors; mechanoreceptors; and gill, kidney, and hematopoietic tissues [14,30]. In addition, exposure to copper has resulted in reproductive effects, such as reduced egg production in females and abnormalities in newly hatched fry [30]. Dietrich and Gallagher [12] reported that sedimentation of runoff from a simulated polyethylene mulch field reduced copper loads by 90%. In our investigation, the implementation of vegetation in the typical bare-soil furrows reduced the average particulate loads by more than 70% (from 6.44 to 1.69 mg/ml in 2000 and from 8.39 to 1.70 mg/ml in 2001) and average copper loads by at least 60% (from 151 to 56 g/ha/runoff event in 2000 and from 60 to 24 g/ha/runoff event in 2001). Copper concentrations in a creek receiving runoff from an agricultural area utilizing plastic mulch were reported to be as high as 22 μg/L, which exceeds the measured median lethal concentration (LC50) for larval clams (*Mercenaria mercenaria*) at 96 h (LC50 = 21 μg/L) and 192 h (LC50 = 12 μg/L) [12]. On the basis of the results of our investigation, implementation of vegetative furrows in these plastic mulch systems could reduce copper loads by at least 60%. Therefore, surface water concentrations could be reduced from 22 to 8.8 μg/L, which is below the LC50, assuming agricultural runoff was the primary copper source. This demonstrates the effect that agricultural management practices can have on water and environmental quality.

Effects of vegetative furrows on production

Production data were obtained from the same plants in each plot over a month-long period. Only star fruit (fruit that has just started to ripen) were chosen. Total yields measured between August 15 and September 4 were 23,821 ± 6,305 kg/ha for BSF plots and 20,443 ± 6,018 kg/ha for CRF plots in 2000 and 38,564 ± 9,651 kg/ha for BSF plots and 40,086 ± 14,024 kg/ha for CRF plots in 2001. No significant difference (LSD, 0.05) in harvest yield was observed within each year; however, 2001 was almost two times more productive (Fig. 6a and b). This difference in productivity might be a function of the cooler weather in 2000.

CONCLUSION

Replacing bare-soil furrows with vegetative furrows significantly reduced soil erosion and improved the sustainability of the conventional polyethylene mulch cultivation practice without affecting harvest yields. Cereal rye planted between polyethylene-covered vegetable beds reduced runoff volume by more than 40% and soil loss with runoff by more than 80%. This was the result of both reduced particulate concentrations in the runoff and the smaller quantity of surface runoff collected from the plots with vegetative furrows.

In addition to improving the sustainability of the polyethylene mulch system, replacing bare-soil furrows with vegetative furrows can reduce the environmental impact of vegetable production. Copper hydroxide is the most widely used fungicide/bactericide for tomato production, and it is often applied weekly to prevent or control diseases. Estimated annual use of copper for fresh-market tomato production throughout the United States is 342,009 kg of active ingredient [4]. Copper has been shown to have adverse effects on aquatic organisms, including a reduction in the survival of macroinvertebrates [13] and structural and functional effects on the nervous system of fish [14]. Copper is primarily transported in runoff with suspended particulates; therefore, implementation of management practices that minimize soil erosion should reduce copper loads. In our investigation, planting rye in the furrows between polyethylene-covered vegetable beds reduced total copper loads with runoff by more than 60%. This was primarily the result of reduced soil erosion because more than 88% of the total copper loads were transported in runoff with suspended particulates for both the polyethylene/bare-soil and polyethylene/rye plots. Overall, replacing the bare-soil furrows of conventional polyethylene

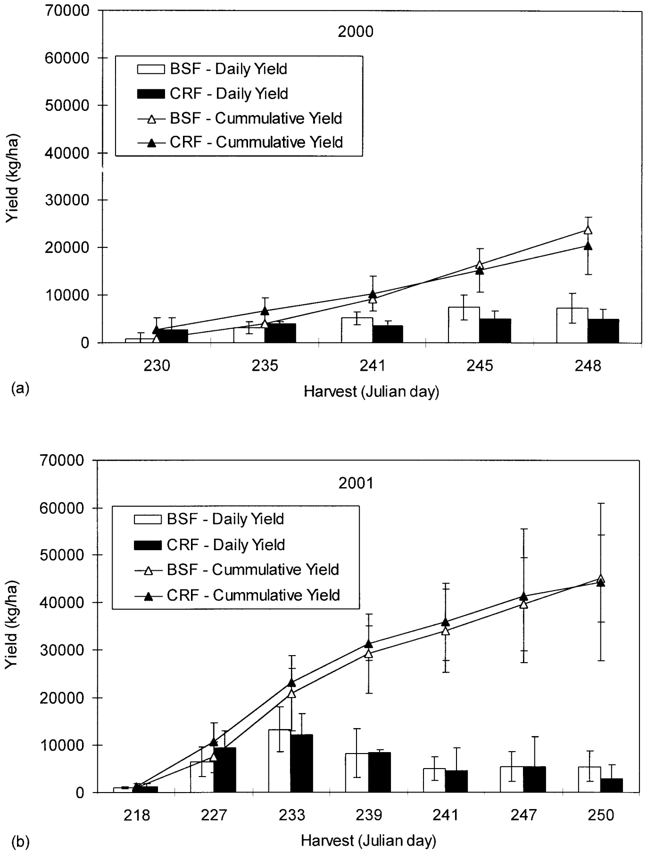

Fig. 6. Daily and cumulative tomato yields from the polyethylene mulch/bare soil furrow (BSF) plots and polyethylene mulch/cereal rye furrow (CRF) plots for the 2000 (**a**) and 2001 (**b**) growing seasons. Error bars represent the standard deviation of the means. Daily or cumulative harvest yield showed no significant difference (LSD, 0.05) between plot treatments.

mulch systems with vegetative furrows will increase the sustainability of this management practice and reduce its environmental impact while maintaining sufficient crop yields to provide growers with an acceptable economic return.

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