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Mulching Practices and Innovations for Warm Season Vegetables in Virginia and Neighboring States

2. results of on-farm field trials in 1993-94

Mark Schonbeck
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Virginia Association for
Biological Farming
P.O. Box 10721
Blacksburg, VA 24062-0721

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This research was conducted as part of a project entitled **Evaluation of Recycled Paper Film Mulch and Organic Mulches as Alternatives to Black Plastic Mulch in Vegetable Horticulture.** This work is supported by a grant from the Southern Region Sustainable Agriculture Research and Education (SARE) program of the United States Department of Agriculture, awarded to the Virginia Association for Biological Farming for 1993-95.

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Summary

Field trials were conducted on five biologically managed farms in Virginia to evaluate paper and organic mulches as sustainable alternatives to black plastic film for warm season vegetables. Information was also retrieved through library research to aid interpretation of our findings and estimate some environmental impacts of different mulching systems.

All mulches tested substantially improved yields of paste tomatoes in most experiments. Mulching was especially beneficial during hot, dry conditions.

Hay and straw mulches spread several weeks after planting at 7.5 tons per acre (about five square bales per 100 feet of crop row) lowered afternoon soil temperature and slightly delayed maturity, but generally gave high yields. These mulches conserved soil moisture, suppressed weeds 50 to 85 percent, and were more labor-efficient than plastic or paper mulches for non-mechanized operations. Production of these materials is fairly energy-intensive. However, many studies over the past 60 years have amply confirmed that hay, straw and other organic mulches confer substantial long-term benefits to soil tilth and soil life.

Composted yard waste (mostly tree leaves) at a 2-inch depth (~100 tons per acre) did not control weeds as well as hay or straw, and was much more labor-intensive to apply.

Embossed black polyethylene mulch applied before planting slightly warmed the soil, and gave significantly higher *early* tomato yields than hay or straw. However, *total* yields were not higher in plastic than in organic mulches, except where late blight occurred. Almost no weeds came through the plastic itself, but weeds in alleys between plastic mulched rows must be controlled by hoeing, organic mulch or other means. Plastic sometimes lowered soil moisture levels by excluding rainfall, but it has the potential of optimizing moisture levels when used with drip irrigation. Plastic mulching is the most energy-intensive system tested, it produces a non-recyclable waste, and does not feed the soil, unless alleys are mulched with organic materials. Earthworm populations were only half as high under plastic as under hay.

Recycled kraft paper was tested, both untreated and treated with vegetable oil. Paper tended to decompose too quickly, resulting in weed problems, slightly less moisture conservation than hay, and sometimes lower yields. Untreated paper somewhat cooled the soil, but oiled paper raised soil temperatures several degrees more than plastic early in the season. Manufacture of recycled paper is less intensive than plastic, and *removes* material from the waste stream. Using waste paper directly further saves energy.

A combination mulch of oiled paper before planting followed several weeks later by hay was tested in an effort to gain benefits of both plastic (early yield) and hay (organic matter). However, tomato yields in this mulch were the same as in hay alone: high but somewhat late. The combination mulch conserved nearly as much moisture, and supported as many earthworms as hay by itself.

A mowed winter rye + hairy vetch cover crop was tested at one site as an *in situ* mulch. However, the residue produced was insufficient, resulting in poor weed control and moisture retention, and low crop yields. Very high yields in this system in some other studies indicate it may have considerable potential once management methods are refined.

Introduction

The Virginia Association for Biological Farming (VABF) is conducting a comparative study of different mulching systems for warm-season vegetables. Mulches suppress weeds, conserve soil moisture, and can improve crop yield or quality. Organic mulches such as hay, straw or leaves enhance soil tilth and organic matter, but they can lower soil temperatures and thereby delay maturity in warm-season crops like tomatoes and cucumbers. Plastic film mulches such as black polyethylene (PE) offer superior weed control, earlier harvests and the option of mechanized application, but they do not add organic matter, and must be picked up and disposed at the end of the season. Paper mulches may offer some of the advantages of plastic, yet are biodegradable and do not require disposal. Mulching systems that help maintain or improve the soil while supporting adequate and timely crop yields are needed for sustainable vegetable production.

Choice of mulching system is farm-specific, and depends on climate, soil, crops grown, availability and cost of mulching materials, labor and machinery, market opportunities and constraints, and the grower's farming philosophy. The goal of this project is to assist farmers and gardeners in optimizing their mulching practices by providing information on the effects of different mulches on crop performance, weed control, soil conditions, pests and diseases, and other benefits and costs, including environmental impacts. This information was gathered from three sources: growers' experience, on-farm field experiments, and relevant literature.

During 1993-94, VABF conducted field experiments on five working farms to evaluate sustainable alternatives to plastic film mulch. A literature search was also conducted to retrieve relevant information that may not be readily available to growers, and to estimate energy and environmental costs associated with different mulches. The following report presents the findings of this research. A grower survey on mulching practices in this region is summarized in a companion report (*52*). (**Note:** numbers in italics in parentheses indicate references listed at the end of the report)

Rationale and Methods

Plastic, paper and organic mulches were evaluated on tomatoes at two biological farms in Virginia in 1993 and five farms in 1994 representing a range of climates and soils (Table 1). Black PE and hay were tested at all sites, and an unmulched control was included in four experiments to help estimate the net benefits of mulching. Grain straw was tested in 1994 based on growers' observations that it is faster draining and slower to decompose than hay, and thus might keep the fruit cleaner (*52*). We evaluated compost as a mulch because of its known benefits to the soil and possible disease-preventive activity. Also, municipal waste composting facilities may provide materials for nearby farms, and municipal composts have been explored as an alternative to black plastic in large-scale pepper and squash production in Florida (*40, 48*). An *in situ* mulch of mowed cover crops was evaluated at Site 1 where the grower normally uses this practice for tomatoes. This system may be more feasible for larger farms than spreading hay or other organic materials, and improved equipment for transplanting vegetable starts through cover crop residues is becoming available (*42*).

Table 1. On-farm Experimental Sites and Treatments

Site No.	County	Region	Soil type	Frost dates: spring	Frost dates: fall
1	King & Queen	Coastal Plain	Loamy sand	Apr 17	Oct 17
2	Loudoun	Blue Ridge foothills	Sandy loam	Apr 25	Oct 8
3	Louisa	Piedmont	Loam	Apr 20	Oct 20
4	Floyd	Appalachian Plateau	Silt loam	May 15	Oct 5
5	Floyd	Appalachian Plateau	Sandy loam, stony	May 25	Oct 5

Year & Site No.	Treatments								
	Black Plastic	Paper [a]	Oiled Paper [a]	Hay	Straw	Compost	Oiled Paper + Hay	Mowed Cover Crop	Bare Soil
1993									
3	X	X		X[b]					X
5	X	X		X					X[b]
1994									
1	X			X[b]		X	X[c]	X[b]	
2	X	X	X	X	X[b]	X	X		X
3	X			X[b]	X		X[c]		
4	X	X	X	X[b]	X	X	X		X
5	X	X	X	X			X		[b]

[a] 65-lb recycled kraft paper in 1993 and at Site 5 in 1994; 40-lb recycled kraft paper at all sites in 1994. Oiled paper was 40-lb.
[b] grower's practice.
[c] originally intended as oiled paper alone; hay was added as "rescue" treatment when the paper failed in early summer. See text.

Paper and vegetable oil-treated paper mulches derived from recycled wastes were tested as biodegradable and environmentally friendly alternatives to plastic film. Mulch papers were developed and used early this century before plastic films became available, and were reported to improve yields of some vegetables (*41, 59*). Paper tends to decompose too rapidly, but oiled paper may last longer, and warms the soil better than untreated paper (*5*). A combination of oiled paper followed several weeks later by hay was explored as a means to derive the benefits of both plastic (soil warming) and hay (organic matter).

The plastic used was four foot wide, 1.25 mil embossed black polyethylene (PE) mulch. Paper mulches consisted of four foot wide rolls of 100% recycled (40% post consumer) kraft paper in 65-lb and 40-lb grades (weights per 3,000 square feet), similar in color and texture to heavy duty and regular shopping bags, respectively. Oiled paper was prepared by submerging 25-foot long rolls in waste cooking oil from a local restaurant for 12 hours, then allowing them to drain for two days.

Hay and straw were spread at about 7.5 tons dry weight per acre (= one 35-lb square bale per 100 square feet). The straw bales used at Site 4 were lighter than usual, resulting in an actual rate of 5.3 tons per acre. Composted yard waste (mostly tree leaves) was obtained from a facility near Richmond, VA and spread about two inches deep (~ 100 tons per acre). At Site 1, winter rye + hairy vetch sown the previous fall was mowed 18 days before planting. Tomatoes were transplanted either directly through untilled cover crop residue, or into a 20-inch wide tilled strip running down the center of the plot. Cover crop regrowth was clipped twice during early summer. The cover crop produced about 1.5 tons dry mulch per acre.

At each site, the soil was prepared and amended according to the growers' usual practices, and 'Roma' paste tomatoes were transplanted after the last frost in rows five feet apart, except eight feet at Site 3. Crops were grown without staking, irrigated and weeded as necessary, and harvested on the farmer's normal schedule. Mulch treatments were replicated three times at each site in small plots consisting of 25 feet of a single row.

Black PE and paper were laid just before planting. The soil was raked smooth and level, a 4-inch deep furrow was dug around the plot perimeter, and the mulch was laid and anchored by refilling the furrow with soil. A sharpened bulb planter was used to cut 3-inch diameter circular holes in the film, through which seedlings were planted. Plot margins not covered by the film were left bare in 1993, but were mulched with hay or straw in 1994.

For organic mulches, the soil was worked lightly to remove large ridges, stones and clumps of residue before planting. At Site 3 in 1993, hay was spread at planting time. In all other experiments, organic mulching was delayed two to five weeks after planting to let the soil warm up, and weeds were hoed just before mulching. Bare soil plots were managed on the same schedule as organic mulch plots, except no mulch was applied.

Soil temperatures were measured weekly from planting until about four weeks after organic mulches were laid. Readings were taken at a depth of four inches in the early morning and mid to late afternoon. At early fruit set, soil cores (0 to 12 inches) were taken to determine moisture percentage (lb water per 100 lb dry soil) and soluble soil nitrogen (N). Foliage samples were also collected to measure crop N concentration.

Mulches were observed throughout the season to determine how well they maintained ground cover and suppressed weeds. Weeds were pulled as needed, and weighed. Supplemental experiments were also conducted in Floyd County to compare oiled and untreated kraft papers with hay, bare ground, and Planters' Paper, a commercially available black 32-lb recycled kraft paper mulch. (**Note:** mention of a specific product or trademark does not imply recommendation by the authors or VABF of that product over others). Mulch was laid in miniplots (4 by 6 feet), and planted with tomatoes (1993) or pickling cucumbers (1994). Mulch breakdown, weed biomass and soil temperatures were recorded.

Tomato vegetative growth was estimated by canopy width measurements. Pest and disease outbreaks were rated in each plot, and treated with natural controls when necessary. Tomato fruit were harvested at the red-ripe stage, and marketable yields were recorded. "Early yield" was defined as the first three weeks of harvest. Fruit size, percent soluble solids (a measure of quality), and incidence of hollowness and other defects were recorded in some experiments.

At the end of the season, soil samples were taken to determine moisture content, bulk density (a measure of soil compaction), water infiltration rate and aggregate stability (an indicator of tilth or structure). Earthworm populations were estimated by counting individuals in one or two randomly selected 1-foot square x 6 inch deep soil samples in each plot.

Plots were managed by manual methods, and operations directly related to mulching system were timed to compare labor costs. These include final soil preparation, planting, mulching and weed control. Purchase costs for materials in bulk were obtained from catalogues (*23, 44*) or from estimates by growers (*52*). Energy costs of producing each mulching material were estimated from existing information on farm operations (*28, 32, 46, 55, 62*), and plastic and recycled paper production processes (*15, 21, 46*), and converted to gallons of diesel fuel per acre.

Yields and other data were analyzed using standard statistical methods (*56*) to distinguish differences that probably reflect an actual effect of mulching (significant) from those that may arise by chance (non-significant). It is impossible to be *certain* that a given difference indicates a treatment effect because of random variation in field conditions, plant vigor, mulch thickness or accuracy of data collection. In this study, a least significant difference (LSD) for each data set was determined at the 5% probability level, meaning there is only a 5% chance of falsely identifying a treatment effect when no such effect exists.

Results

Mulch Persistence and Weed Suppression

Black PE mulch remained intact throughout the season, except when damaged by deer at Site 2. In 1993, untreated 65-lb kraft paper began to break down in summer, but still covered 75% to 85% of the soil surface in late August. The 40-lb paper held up slightly better than the commercial black paper mulch, and oil treatment significantly delayed decomposition.

In 1994, both oiled and untreated 40-lb paper failed early in the season, as weeds grew under the paper, pushed it up and tore it loose. At Sites 2 and 4, the largest weeds were clipped and the paper was weighted with stones. At Sites 1 and 3, hay was added to hold oiled paper in place and suppress weeds (Table 1).

Hay began to decompose toward the end of the season, but still covered 80% to 90% of the ground in mid to late August, and reduced weed biomass (dry weight per unit area) by 50% to 85% compared to bare soil. Straw performed similarly to hay, except at Site 4 where the lower application rate allowed more weed growth. Weed biomass in oiled paper + hay was generally similar to hay alone. Compost maintained good cover (≥90%) throughout the season, but did not suppress weeds as effectively as hay, probably because its loose, crumbly texture offered less resistance to emerging seedlings. The mowed cover crop at Site 1 was insufficient to suppress weeds, as ground cover decreased to about 50% by mid June.

Black PE-mulched plots often had higher weed biomass than hay plots, but most of the weeds occurred in plot margins not covered by film, with just a few weeds growing through planting holes. The margins were left bare in 1993, and mulched with hay at planting at four sites in 1994. Much of this hay broke down or blew away by midsummer, allowing weeds to grow. At Site 5, alleys were hoed and hay-mulched several weeks after planting, which seemed to eliminate the problem. However, weed pressure was so light at this location in 1994 that no manual weeding was required in any treatment. Weed biomass in untreated or oiled paper was similar to that in plastic, although more weeds came through the paper itself.

At Site 4, all mulches were more effective against annual broadleaf weeds (mostly common ragweed and jimsonweed) and grasses than against horsenettle and other broadleaf perennials. In the miniplot experiment established at the end of June, an intense growth dominated by common ragweed choked out unmulched cucumbers, but both paper and hay effectively controlled weeds.

All paper mulches became detached from the soil by 56 days after planting, but were held in place by the cucumber vines. The 65-lb kraft paper maintained better ground cover and weed control than 40-lb paper, and oil treatment slowed decomposition of both. Oiled papers transmitted 17% to 29% of incident light compared to 1% to 12% for untreated paper, but high temperatures under oiled paper (>100°F) killed emerging weeds. Black paper decomposed as fast as 40-lb paper, but gave better weed control (99% *vs* 90%) probably because it blocked light more effectively early in the experiment.

Soil Temperatures

Both black plastic and oiled paper enhanced afternoon soil warming and retained some of the accumulated heat overnight, resulting in higher morning soil temperatures as well (Table 2). During the first few weeks after application, afternoon soil temperatures were several degrees higher under oiled paper than plastic, but this effect diminished later as the paper began to decompose. Untreated paper significantly lowered afternoon soil temperature.

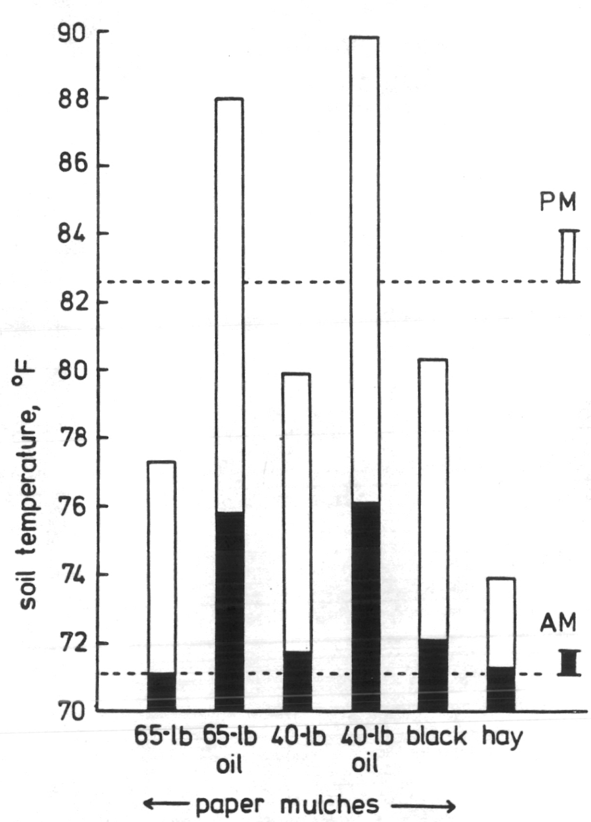

Figure 1. Morning and afternoon soil temperatures under five paper mulches and hay mulch, compared to bare soil (horizontal dotted lines). Small bars at right show least significant difference (LSD).

Table 2. Effects of Different Mulches on Soil Temperature [a]

Mulch	*Temperature under mulch – temperature in bare soil, °F* 1 to 30 days after planting AM	PM	1 to 31 days after organic mulch application AM	PM
Black plastic	+4.0 *	+2.5 *	+3.1 *	+2.0 *
Paper	+0.1	–4.5 *	–0.2	–3.0 *
Oiled paper	+4.4 *	+7.0 *	+2.0	+1.2
Hay			+0.9	–6.8 *
Straw			–0.4	–6.9 *
Compost			+1.6 *	– 2.5 *
Average temperature of bare soil, °F	*62.8*	*77.5*	*68.7*	*79.4*

[a] Measured at a depth of four inches. Each comparison is based on two or more experiments in 1993 and 1994.
* Significantly different from bare soil.

Hay and straw lowered afternoon soil temperatures nearly 7°F but had little effect on morning temperature. Compost buffered temperature fluctuations, keeping the soil warmer in the morning but cooler in afternoon than bare soil. Compost maintained higher soil temperature than hay, probably because of its darker color.

Soil temperatures were no higher under black paper than under untreated 40-lb kraft paper, and significantly lower than under oiled paper (Figure 1). The 65-lb paper kept the soil slightly cooler than the less opaque 40-lb paper, but oil treatment resulted in dramatic temperature increases under both.

Soil Moisture, Physical Properties and Earthworm Populations

During the hot, dry 1993 season, hay mulch conserved soil moisture better than other treatments. At Site 3, the unmulched plots were severely depleted of moisture in June, while plastic hindered entry of fall rains, resulting in low levels in October (Figure 2). At Site 5, soil moisture was about 2% to 3% higher under hay than plastic, with paper and bare soil intermediate.

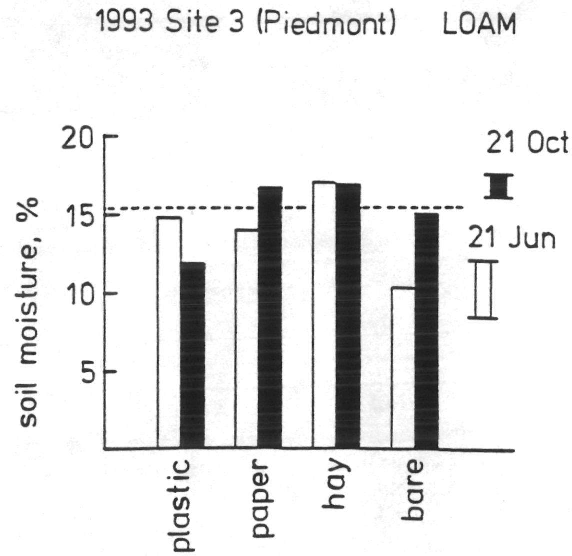

Figure 2. Summer and fall soil moisture levels under three mulches and in bare soil in 1993 at Site 3. Small bars at right show LSD.

During the wetter summer of 1994, soil moisture was significantly lower under plastic than under hay (Table 3). At Site 1, poor ground cover by mowed rye + vetch resulted in summer moisture depletion similar to plastic. In the fall, the sandy soils at Sites 1 and 2 remained drier under plastic than under organic mulches, but the loam at Site 3 was equally moist in all mulches. At the two Appalachian sites, fall soil moisture levels were actually higher under plastic than in bare soil and in paper or straw mulches which had deteriorated sufficiently to leave much of the soil exposed. Moisture can move laterally through fine-textured soils like the silt loam at Site 4; thus autumn rains apparently recharged soil moisture under the plastic, which then prevented losses by evaporation.

In most experiments, soil moisture under paper and oiled paper was somewhat lower than under hay. Some moisture was probably lost because the paper broke down quickly; also oiled paper may have somewhat repelled incoming rainfall.

At the end of the season, soil bulk density measurements revealed no significant differences between treatments in soil compaction. At Site 4, water infiltration was slower after compost or oiled paper than after plastic, but this was not observed at other sites, and the cause is not known. Aggregate stability measurements (index of tilth) are not yet completed. Earthworm populations were higher under hay or paper than under plastic at Site 3 in 1993. In 1994, hay and oiled paper + hay had twice as many worms as plastic (Table 3). Possible reasons for this trend include higher soil temperature or lower moisture levels under the plastic, as well as the fact that the worms can eat hay or paper, but not plastic.

Crop Growth, Yield and Quality

Early in the season, tomatoes in plastic or oiled paper grew somewhat faster than plants in other treatments, but plants in organic mulches caught up later in the summer. In 1993, tomatoes in bare soil were severely stunted and recovered only partially by August. In 1994, unmulched border row plants in the sandy soil at Site 1 also grew poorly, while unmulched plants were only slightly smaller than others at Sites 2 and 4 . At Site 4, soil soluble N at early fruiting was much higher under plastic or oiled paper than other mulches. At other sites, soil soluble N measurements varied erratically between "not detectable" and over 40 ppm (a high level). Tomato foliar N was slightly lower under plastic or oiled paper than other treatments at Site 2, but was unaffected by mulch at other sites. However, tomato foliar N exceeded 4.0% in all treatments and sites, indicating ample N available to the crop (7).

Table 3. Soil conditions, tomato yields and late blight under plastic, hay, and oiled paper + hay mulches in 1994.

	Plastic	Hay	Oiled paper + hay
Soil Conditions, mean for all sites:			
Temperature, °F [a]	78.2	73.0 *	72.3 *
Moisture, summer, % [b]	14.3	19.4 *	18.1 *
Moisture, fall, %	20.4	20.2	20.7
Earthworms per square foot, fall	7.1	14.1 *	13.5 *
Marketable Yields for Sites 1, 2 and 3 (not affected by late blight):			
First 3 weeks, tons/acre	6.0	3.4 *	3.7 *
Total, tons/acre	21.4	24.1	25.0
Marketable Yields and Fruit Blight for Sites 4 and 5 (affected by late blight):			
Total, tons/acre	4.4	2.3 *	3.5
Percent of fruit with late blight	34	48 *	38

* significantly different from plastic

[a] mean of morning and afternoon soil temperatures at 4 inch depth, measured on several dates from 1 to 30 days after hay application.

[b] mean for sites 1-4, as summer soil moisture was not measured at Site 5.

In 1993, black plastic, kraft paper and hay mulches all enhanced total marketable yields compared to bare soil (Figure 3A). Tomatoes in hay yielded slightly better than in paper. Early yields were significantly higher in plastic than hay or paper, but this was not true for total yields. Similar trends were noted in 1994 at Sites 1, 2 and 3 (Figure 3B, Table 3). Total yields tended to be slightly higher in organic mulches than plastic, although this difference was not statistically significant. Mulching system had little effect on fruit size, percent marketable fruit, percent soluble solids, and incidence of hollowness, cracking, insect damage or other blemishes.

Yields were depressed in mowed rye + vetch at Site 1, probably because conditions approached those of bare soil, with excessively high soil temperature during hot days, poor moisture retention and heavy weed pressure. Competition from cover crop regrowth may also be a factor, but strip tillage did not improve yield.

Late blight severely affected crops at the two Appalachian sites in 1994. Seaweed extract, compost extract and copper fungicide were applied beginning at the onset of symptoms, but frequent rain washed off the sprays and helped spread the disease. At Site 4, late blight destroyed the crop by August 10, and all fruit over 2 inches in length were harvested, separated into visibly blighted and unblighted, and weighed. Nearly all unblighted fruit were successfully sun-ripened over the next four weeks, and were recorded as marketable yield. At Site 5, a small yield of marketable ripe fruit was harvested. At these two sites, hay-mulched plants had a higher percentage of blighted fruit and a lower marketable yield than plants in plastic (Table 3). Yields and blight levels in other organic mulches were similar to hay, while paper, oiled paper and oiled paper + hay were intermediate.

Mild outbreaks of early blight occurred at Sites 2, 3, 4 and 5, but fruit were affected only at Site 5. This disease damaged more fruit in plastic and paper mulches (2% to 4%) than in hay or oiled paper + hay (<1%).

The combination of oiled paper before planting followed by hay several weeks later was designed to promote early yields while realizing the benefits of organic mulch. However, despite early-season soil warming by oiled paper, both soil temperature after hay application and early yield were similar to hay alone (Table 3). Soil moisture conservation, earthworm numbers and total yield were also similar for these two treatments (Table 3). At the sites affected by late blight, oiled paper + hay gave marketable yield and blight levels that were intermediate between plastic and hay.

Few insect pest problems occurred. Stalk borers attacked some seedlings at Site 4, necessitating replacements and several applications of Bt. Light to moderate infestations of Colorado potato beetle at Sites 1, 2 and 3 were hand-picked, and potato aphids were observed at Site 3 but did not cause much damage. Although plastic mulch plots tended to have more potato beetles than hay or straw, the difference was not statistically significant.

In the miniplot experiment in 1994, cucumber vines grew significantly faster in oiled paper than other mulches. A severe outbreak of downy mildew curtailed harvest, but the crop yielded more in oiled paper than untreated paper.

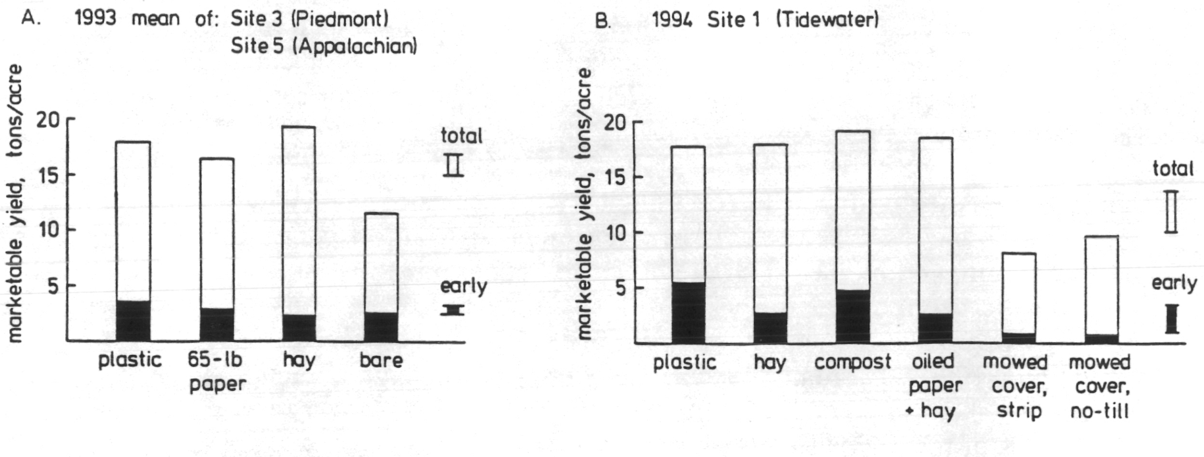

Figure 3. Early and total marketable tomato yields in various mulches in 1993 (A) and at Site 1 in 1994 (B). Small bars at right show LSD. *Note:* 20 tons per acre = about 460 lb per 100 feet of row, if rows are 5 feet apart.

Labor and other costs

In 1993, mulching with hay saved as much time in weed control as was consumed in applying the mulch itself, so that total time for manual operations (final soil preparation, planting, mulching and weeding) was similar for hay and bare soil. In 1994, each hour spent mulching with hay saved two to five hours weeding. Plastic and paper mulches took much longer to apply than hay or straw (Table 4) and also required a little more time and care in soil preparation and planting. Overall, hay was more labor-efficient than plastic or oiled paper + hay (Figure 4), and total yields were not significantly different (Table 3).

Straw was as time-efficient as hay except at Site 4 where insufficient thickness led to more weeds. Compost required much longer to apply than hay (Table 4), and also more weeding labor. Paper mulches required similar amounts of time as plastic for application and planting, but early breakdown and loss of weed control could add to labor costs.

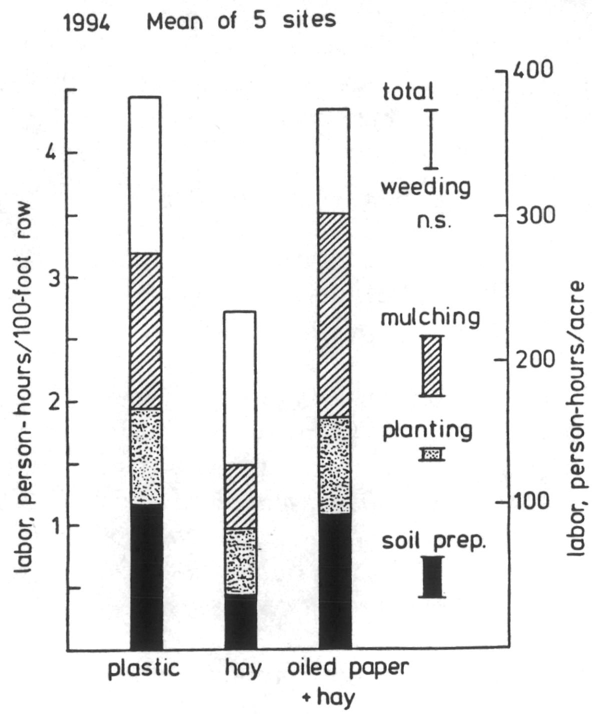

Figure 4. Labor required for final soil preparation, planting, mulching and weed control in three mulching systems in 1994. Small bars at right show LSD; n.s. = differences not significant.

Labor estimates by growers in the survey averaged 90 hours per acre (just over 1 hour per 100 feet of row) for hay and straw, and only 82 hours per acre for plastic films. Estimates in our field trials did not include time for hauling mulch materials to the field, which could be significant for bulky organic materials. Also, many growers used less labor-intensive methods for securing film mulches, e.g. a shovelful of earth every few feet rather than burying the entire margin in the soil.

Purchase costs were higher for black mulch paper, plastic, hay and straw than for recycled kraft paper mulches (Table 4). Plastic represents the largest per-acre energy input for materials, followed by hay or straw. Recycled paper mulch is more energy-efficient because making paper from recycled fiber (post consumer and/or factory trimmings) saves about 60% on energy compared to paper from virgin fiber (*21*). Energy consumed in producing cover crop seed is comparatively small. Mechanized applications (e.g. machine-laying plastic, applying compost by manure spreader, or broadcasting and disking cover crop seeds) require at most a few gallons of tractor fuel per acre (*32*).

The waste generated as a result of plastic mulching has become a significant waste disposal concern (*29*). In contrast, use of recycled paper mulches effectively removes materials from the waste stream as well as making a small contribution of organic matter to the soil (Table 4). Hay and straw do not directly affect the waste stream but contribute much organic matter.

Table 4. Per-acre direct costs and environmental impacts of mulches tested in field trials.[a]

Mulch treatment	Purchase cost, $/acre	Application labor, hours/acre [b]	Energy cost, of materials, diesel fuel equiv., gal/acre	Organic matter added, lb/acre	Impact on waste stream, lb/acre
Black PE, 1.25 mil	417	134	320	0	+ 210
40-lb recyc. kraft paper	153	112	44	464	– 186 [c]
65-lb recyc. kraft paper	242	108	72	755	– 302 [c]
Oiled 40-lb paper	153	116	44	909	– 631 [c]
Planter's Paper	552	~ 110	35	371	– 148 [c]
Hay, 7.5 tons/acre	510 [d]	52	126	15,000	0
Straw, 7.5 tons/acre	711 [e]	52	155	15,000	0
Oiled 40-lb paper + hay	663	156	170	15,909	– 631 [c]
Mowed rye + vetch	40	~ 40 [f]	6	3,000	0
Composted leaves	g	153	g	g	– 100 *tons*

[a] For costs per 100 feet of crop row, divide by 87.
[b] From on-farm trials. Not measured for Planter's Paper; assumed same as kraft papers.
[c] All recycled papers assumed 40% post-consumer; waste cooking oil used at 0.96 lb per lb paper (*5*).
[d] Average price of $1.19 per bale (*52*).
[e] Average price of $1.66 per bale (*52*).
[f] Sickle-bar mowing cover crop before planting, plus clipping cover crop regrowth.
[g] Data not yet obtained; organic matter content of compost can vary from 20 to 75%.

The effective energy cost of mulching may be drastically reduced when locally-available waste materials are used that would otherwise be discarded. Examples include: reject or end rolls from paper mills and printing presses, yard waste and other compostable municipal wastes, spoiled hay that would not otherwise be utilized, and sawdust. The use of compostable municipal wastes as a mulch could potentially divert up to 100 tons of waste from landfills for each acre mulched. However, both direct and environmental costs of transporting such large masses of material from source to farm could be prohibitive unless the distance is small.

Estimates of net returns on plastic, paper and organic mulching systems, based on results of field trials and the data in Table 4, indicate that all three paid for themselves even at wholesale tomato prices (Table 5). For direct-marketed tomatoes, the returns are quite substantial. Additional benefits may include labor saved on weeding (though increased harvesting labor resulting from heavier yields might partially offset this), and replenishment of soil organic matter and tilth in the case of organic mulches.

Table 5. Estimated net returns for plastic, paper and organic mulching systems in tomatoes.

Mulching system	Direct costs $/acre [a]	Average yield increase, tons/acre [b]	Net return, $ /acre for: Wholesale ($0.33/lb) [c]	Retail ($1.00/lb) [d]
Black plastic	1,221	3.8	1,287	6,379
Paper	864	2.9	1,050	4,936
Hay, straw	922	5.2	2,510	9,478

[a] Purchase costs plus labor (Table 4) at $6.00 per hour.
[b] Compared to bare soil; mean of Sites 3 and 5 in 1993, and Sites 2 and 4 in 1994.
[c] Virginia Agricultural Statistics, 1993.
[d] Typical price at Blacksburg, VA farmers' market in 1994.

Other Relevant Findings

Mulching and weed control

Plastic, paper and organic mulches all significantly reduce weed growth in studies comparing them with bare soil. Opaque or infrared-transmitting (IRT) plastic films stop nearly all weeds in the crop row (*16, 38*), but alleys not covered by plastic usually require cultivation, cover cropping, mowing, organic mulches or herbicides. Organic mulches suppress weeds in proportion to their thickness. A four-inch layer of straw or pine needles has been found effective (*16, 54*) whereas two inches is insufficient and may even encourage weeds (*6*). As little as 1.5 to 3 tons wheat straw per acre have significantly reduced weed growth (*20, 43*), but much more is needed for satisfactory weed control. Our results and information gathered in the grower survey indicate that, for biologically managed vegetables in this region, 7.5 to 10 tons per acre of hay or straw is sufficient to save considerable labor on weed control.

Hay mulch is sometimes not recommended because of weed seed content (*54*). In our study, grassy weeds from hay-borne seeds were observed in only two of nine experiments. At Site 1, hot, dry conditions prevented these weeds from becoming established. In the cucumber experiment at Site 4, significant grass weed growth resulted, but was far less intense than common ragweed growth in bare soil. Organic and paper mulches seem quite effective against this and most other annual weeds, but less so against redroot pigweed and perennial weeds (*43*).

In our field trials, two inches of a loose-textured leaf compost gave only partial weed suppression. However, the same depth of composted municipal wastes effectively controlled weeds in Florida (*47*). This compost had a high paper content and formed a crust after wetting, which blocked emerging weeds.

A single layer of 40-lb or 65-lb kraft paper reduced weed growth somewhat, but weeds broke through as the paper decomposed. Four thicknesses of newspaper have given similar results, while shredded newspaper at 3.4 tons per acre appears to be more effective (*16, 43, 54*). Clear plastic acts similarly to oiled paper in that it permits weed growth by transmitting light (*38, 54*), but may kill the weeds by solarization in hot weather.

Many growers who use organic mulches on summer vegetables wait several weeks after planting to let the soil warm up, hoe or cultivate, then spread the mulch. Critical times for weed control seem to be four to five weeks after transplanting tomatoes (*7, 64*), and two to five weeds for cucumber (*25*). A single hoeing followed by mulch at this time may be sufficient to prevent weeds from hurting vegetable yield, and may also be a good strategy for alleys between plastic-mulched beds.

Weeds reduced tomato yields in mowed rye + vetch at Site 1 (Figure 3B), and some researchers recommend postplant herbicides for vegetables planted no-till into mowed cover crops (*3, 31*). However, vetch + rye can produce 3.0 to 4.8 tons mulch per acre, and sometimes control weeds adequately without additional measures (*53, 57*). Reduced tillage, substances released from rye residues, and the physical barrier of the mulch all contribute to weed control in mowed cover crop systems (*66*). Thus adequate weed control may be accomplished with less than the 7.5 to 10 tons per acre suggested earlier for hay or straw, and some growers found that supplementing the cover crop with a light application of these materials is effective (*52*). Recent developments in no-till transplanter technology have improved seedling establishment while practically eliminating soil surface disturbance and thereby reducing in-row weed seed germination (*13, 42*).

Effects of mulches on soil conditions

In various studies, mulching practices affected soil temperatures as follows: clear plastic > black plastic > paper ~ bare soil > organic mulches (*6, 19, 33, 38, 51, 54, 59*). Afternoon temperature increases under clear plastic (6 to 14°F) were similar to those under oiled paper (Table 2, Figure 1). Organic mulches are often reported to depress soil temperature by as much as 10 to 20 °F, but this is usually based on readings taken in the afternoon when the largest differences occur. In some cases, the mulch was very thick and/or was applied at planting. When both morning and afternoon readings are taken into account, our data suggest that a 7.5 ton per acre hay or straw mulch applied several weeks after planting would lower average soil temperatures by only 3 to 4°F.

Organic mulches conserve soil moisture by improving rain infiltration and reducing evaporative losses (*4, 12*). As little as one ton per acre may reduce evaporation from the soil surface by half, and three tons by 80%. Soil moisture percentages (lb water per 100 lb dry soil) range from 1 to 10 points higher under straw, pine needles or other organic materials than in unmulched soil (*6, 16, 22, 33, 43, 51, 65*). Paper also conserves moisture, though often to a lesser degree (*16, 43, 59*), as we also observed (Figure 2). Plastic reduces evaporation, but also blocks entry of rainfall; thus soil moisture levels may be either higher or lower under plastic than in bare soil depending on weather conditions (*6, 16, 51*). Either organic mulch or plastic + drip irrigation may reduce irrigation needs by over 40% (*24, 38*).

Because plastic mulch excludes excessive rainfall, it can reduce the leaching of N, potassium (K), calcium (Ca) and magnesium (Mg), and potentially improve crop nutrition (*35, 39, 48, 58*). However, roots of tomatoes and cucurbits grow much more shallowly under plastic films than in unmulched soil (*36*), which might make the crop more drought-prone or limit efficiency of nutrient uptake under some conditions, unless drip irrigation is provided. Mowed vetch contributes K as well as N to tomatoes, and other organic mulches can also provide K (*18, 26, 37*).

Although the soil benefits of organic mulches are occasionally downplayed, numerous studies over the past sixty years have demonstrated what many vegetable growers already know from experience. Straw and other organic mulches improve soil aggregation, tilth and permeability, prevent runoff and erosion, encourage beneficial microbe and earthworm populations by providing food and protection from temperature and moisture extremes, and maintain or gradually restore organic matter levels (*4, 11, 14, 17, 22, 30, 45, 60*). As little as one ton straw per acre can confer some of these benefits, although three to five tons is better. These studies also show that the presence of *soil surface protection*, and the *process of decomposition of organic residues* are the main factors in protecting and replenishing the soil; thus annual (or more frequent) surface applications are more effective than incorporating organic amendments.

Surface applications are also less likely to tie up N or acidify the soil. Even oak leaf, sawdust and pine needle mulches did not reduce pH in some studies (*11, 16*). However, organic mulch in combination with ammoniac nitrogen fertilizer may promote enough acidification to require liming (*60*).

Both living and mowed cover crop mulches provide the same range of soil benefits (*14, 67*), and their effectiveness is maximized by the greatly reduced tillage in these systems. The year-round presence of active roots also promotes humus formation, particularly when a mixture of legumes and grasses is present.

Paper mulches can also confer some of these benefits, as it protects the surface and provides some organic matter. Plastic is reported to reduce soil compaction (*38, 39*), probably by protecting the surface from raindrop impact; however even a thin straw mulch is much more effective (*60*).

Mulch effects on crop yields

Other studies confirm our findings that plastic, paper and organic mulches all improve tomato yields over bare, cultivated soil (Table 6), even though they have very different effects on soil temperatures. Moisture conservation by the mulch seems to be the primary factor in improving yields (*33, 65*). Soil-cooling organic mulches delay maturity to some extent, resulting in lower early yields even where total yields substantially exceed those for bare soil or plastic mulch (*1, 33, 49*). Delaying mulch application until several weeks after planting, with cultivation just before mulching, has been recommended as it lessens early yield reduction and maximizes total yields.

Tomato yields tend to be higher in organic than plastic mulches in warmer climates such as Maryland (Table 6) and Sites 1, 2 and 3 in our study (Table 3). Tomatoes grow best at a root zone temperature of 75 to 80°F and suffer stress at higher temperatures (*61, 62*), and therefore may benefit from a soil-cooling mulch in hot weather. Thus, tomatoes yielded 18 to 21 tons per acre more in straw (average soil temperature 77°F) than in woven black plastic (average soil temperature 95°F) in a two-year study in Georgia.

Table 6. Yields of tomatoes in different mulching systems compared to a bare-soil control.

		Yield in mulch – yield in bare soil, tons per acre:				
State	Year	Black plastic	Paper	Organic mulches		Source
NY	1928-31		+ 2.3			*59*
WV	1930		+ 0.6			*41*
	1931		– 0.4			
PA	1950			+ 5.0	(corn fodder)	*33*
SC	1975	+ 1.5				*34*
	1976	+ 2.7				
IN	1984-85	+ 11.8				*8*
NY	1986	+ 7.1				*27*
	1987	+8.2				
OH	1990		+ 9.1	+ 5.0	(straw)	*43*
MD	1991	+ 24.1	+ 19.2	+ 33.9	(mowed vetch)	*2, 3*
	1992	+ 3.6	– 2.7	+ 22.3	"	
	1993	+ 3.6		+ 5.8	"	
VA	1993	+ 6.4	+ 4.8	+ 7.8	(hay)	VABF
	1994	+ 1.2	+ 1.0	+ 2.6	(hay, straw, compost)	study
Average increase [a]		+7.5	+ 3.7	+ 11.8		

[a] Each report weighted by number of years of experiments.

Results with mowed cover crop mulches appear quite variable. In contrast with low yields after mowed vetch + rye at Site 1 (Figure 3B), tomatoes responded dramatically to mowed vetch in a three-year study in Maryland (Table 4). More rapid release of N by vetch alone, a somewhat heavier cover crop, and the use of herbicide for later-season weed control all probably contributed to the high yield in this treatment. Tomatoes also had far fewer Colorado potato beetles in mowed cover crops than in plastic, paper or bare soil (*1, 50*). No-till transplanting into mowed cover crops also improved tomato yields during a drought in Pennsylvania (*13*).

Eggplant has yielded better in pine needles, plastic or paper mulch than without mulch (*16*), and both eggplant and pepper seem to benefit from organic mulches in warmer climates (*49*). Studies on melons, cucumbers and summer squash have shown yield increases with black or clear plastic and black paper mulches (*9, 10, 19, 51, 59*), whereas straw sometimes reduces melon yields (*51*). Cucurbits prefer higher temperatures than tomatoes. For example, cucumbers mulched with oiled paper which generated very high soil temperatures (Figure 1) showed increased growth and yield compared to other treatments. Yield effects of mulches on cucurbits appear to be: plastic ≥ organic > bare in warm climates, and plastic > bare > organic in cooler conditions.

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