PLASTIC MULCHING

PRINCIPLES AND BENEFITS

Paul E. Waggoner

Patrick M. Miller

Henry C. De Roo

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PLASTIC MULCHING

Principles and Benefits

Paul E. Waggoner, Patrick M. Miller, and Henry C. De Roo

Mulch is one of the gardener's devices for protecting his plants from the vagaries of weather. It is a substance, as straw, paper, or film, spread upon the soil to protect the roots from drought, heat, or cold. Our purpose here is to discover the range of soil climates that mulching can create and thus understand something of their physics and their effect upon plant growth.

Mulches were common enough three centuries ago so that a special word was coined.

The English word was probably derived from the German vernacular *molsch,* meaning soft and rotten. Thus, the ancient mulch must have been a litter of straw that gardeners found kept the soil cool and moist. With the advent of cheap paper and, more recently, plastic film, these too were spread upon the soil and called mulch.

The climate about the plant is profoundly influenced by the disposition of the radiant energy which comes from the sun and sky. Some of this energy heats the air, some heats the soil and plants, some evaporates water, and some returns as radiation. The disposition of the energy among these accounts at the surface determines the activity of roots through a control of soil temperature and moisture. Diverse coverings on the soil will change the disposition of energy among the accounts, create a range of soil climates, and vary the activity—for good or ill—of the roots and their pests.

The voluminous work on soil coverings has been reviewed by Jacks, Brind, and Smith (1955) in their book, *Mulching.* Our efforts were directed especially to a wide diversity in mulches, to their disposition of energy among the accounts, and to pests as well as plants.

An Essential Experiment

A wide range in the climates beneath mulches was a prerequisite to our studies. If no more than a few degrees difference in temperature could be created, there would be little chance of varying plant response and, hence, little likelihood that our studies would have an interesting outcome. That a wide range is possible was shown by a simple but convincing experiment.

A film of translucent, natural polyethylene 152 μ (microns) thick, a 152 μ film of aluminum bonded to a 152 μ film of polyethylene, and a 38 μ film of opaque black polyethylene provided a range of optical characteristics that seemed bound to change drastically the energy budget. In the autumn of 1957 the films were laid between rows of strawberries on Cheshire fine sandy loam at the Lockwood Farm in

Hamden. The plants were at intervals of 30 cm. or 12 inches in the row and shaded only a small portion of the surface, even the following spring. On two May noons the temperature at a depth of 2.5 cm. or 1 inch was measured with a thermometer thrust into the soil:

	No mulch	Black	Translucent	Aluminum
Cloudy	72° F.	73	80	68
Clear	86	87	103	79

Translucent and aluminum films certainly caused changes in the disposition of energy and in the consequent temperature. These great changes were bound to affect plants. And the familiar black film, which caused no important change in temperature but which certainly caused evaporation to dwindle, provided a nice comparison. This elementary experiment assured us of appreciable differences and an interesting outcome. Then we turned to the dispositions of energy through which the mulches create different climates.

Energy Budgets

Balancing the energy accounts is a useful way of understanding how a climate is produced. Several accounts were established:

R_i = incoming radiation,
R_o = outgoing radiation,
W = evaporation or condensation of water,
A = vertical exchange with the air by conduction and convection,
G = conduction to or from the soil.

The flux densities were expressed in langleys/minute (ly./min.) which are equivalent to calories/(square centimeter × minutes).

No account was established for advection or horizontal exchange with the air. Nor were amounts established for the small quantities of photosynthesis and respiration or the temperature change in plants. Thus, we set down the balanced accounts:

$$R_i + R_o + W + A + G = 0$$

This simple analysis of the distribution of energy permitted us to understand how a range of mulches change the climate near the soil surface.

Black, translucent, and aluminum films

Mulched plots were established for observation of the disposition of energy at the modified surface. A 9.2 × 9.2 m. plot of Cheshire fine sandy loam was plowed and harrowed on August 1, 1958. On August 11 it was raked and rolled with a lawn roller. The bulk density was 1.5 g./cm.^{3} in the top 5 cm.

The plot was divided into four quadrants; on August 16 one was covered by black film and one by aluminum foil cemented to plastic. On September 8 one was covered by translucent film. One quadrant was left bare. The films (described on page 5) were pinned down at intervals of 30 to 90 cm. Although the soil had been rolled, it was not perfectly plane and the film did not touch the soil at all points: air lay between film and soil particles over much of the surface.

The density of radiation of all wavelengths was measured by Gier and Dunkle (1951) radiometers manufactured by Beckman-Whitley. First, a hemispherical radiometer near the plots indicated R_i. Then, a net radiometer was supported 90 cm. above the surface by a boom. The boom was rotated, supporting the meter successively over the centers of the quadrants and minimizing the instrumental error in comparisons between quadrants. The net radiometer did not directly measure the R_o from a single quadrant; rather, it measured the difference between R_i, the incoming radiation and R_L, the outgoing radiation that reached its lower face. The R_L included contributions from the other three quadrants and the surrounding bare soil in addition to the contribution from the quadrant immediately beneath the meter.

Nevertheless, the R_o, outgoing radiation from a large area covered by the same film, could be derived from the observations with the two meters. First one derives the R_L from the observations of R_i made by the hemispherical and of net radiation $(R_i - R_L)$ made by the net meter: $R_i - (R_i - R_L) = R_L$. Then from these R_L above three films and bare soil one estimates by iteration the outgoing radiation above infinite planes covered by one material. This final step is based upon the physical composition of R_L:

$$R_L = 0.88\ R_o + 0.02\ R_{adj\ 1} + 0.02\ R_{adj\ 2} + 0.01\ R_{opp} + 0.07\ R_{sur}$$

where R_o is the outgoing radiation density from the quadrant beneath the meter, and the other subscripts refer to the outgoing radiation from the two adjacent quadrants, the opposite quadrant, and the surrounding bare soil. The coefficients preceding each term in the right hand side are the view factors (McAdams, 1954) appropriate for our arrangement of plots and meters. One begins by estimating R_o for bare soil because the surrounding soil is also bare:

$$R_o = (1/0.88)\ (0.93\ R_L - 0.02\ R_{adj\ 1} - 0.02\ R_{adj\ 2} - 0.01\ R_{opp}).$$

The three observations of R_L above the films are substituted in the last three terms of the equation. Then the process of estimation proceeds to the films until one has obtained estimates of R_o from three infinitely large surfaces covered by film and from bare soil.

The W, energy used in evaporation, was estimated by the loss of weight from soil-filled aluminum cans 3 cm. deep and 7 cm. in diameter. One or two cans were set in each quadrant with their surfaces within 3 mm. of the adjoining soil surface. The bottom of the can was found to have a temperature within 1° C. of the soil at the same depth. The surface temperature of the soil in the can was within the range of that of the adjoining surface. At the beginning of each series of observations, the cans were filled with soil from the adjacent field and, hence, had a moisture content near that of the adjacent surface. Evaporation from the soil beneath the plastic films was a small fraction of that from the open soil, was related to the proximity of slits, and was set equal to zero except following a rain. During the day evaporation for any minute was estimated by distributing the observed loss from the open soil according to the course of net radiation. At night the evaporation for any minute was estimated by distributing the observed loss uniformly.

The G, conduction to and from the soil, was measured by heat flow transducers inserted into the profile at a depth of 1 cm. Transducers were placed near the center of the quadrants covered by black and aluminum film, and two were placed near the centers of the exposed quadrant and of the quadrant covered by clear film.

The transducer observations of G were compared, as a check, with the vertical temperature gradient in the soil. The coefficient of conduction was calculated from the transducer estimates of G and from the difference in temperature $\triangle T$ for the difference in depth $\triangle z$ between 1 and 3 cm.

$$K_{soil} = \frac{G}{\triangle T/\triangle z.}$$

The K_{soil} for moist sandy loam has been estimated near 1/4 (ly./min.)/(°C./cm.) (Kersten, 1949). Reasonable and fairly constant values of K_{soil} indicate realistic estimates of G.

The G also was estimated from the diurnal range of the temperature course at a depth of 3 cm. Following Schmidt, the diurnal warming is assumed to follow a sine curve, and the quantity of heat stored per unit area of soil is:

$$\Sigma G/A = (\text{Diurnal range}) \left(\frac{(\text{length of period}) K_{soil}\ C}{2\pi}\right)^{1/2}$$

where C is the heat capacity of the soil. The coefficients have been set equal to those observed on September 12:

$$\Sigma G/A,\ \text{cal./cm.}^2 \text{ or langleys} = (\text{Diurnal range}) \left(\frac{24 \times 60 \times 0.10 \times 0.50}{2\pi}\right)^{1/2}$$
$$= 3.4\ \text{Range}$$

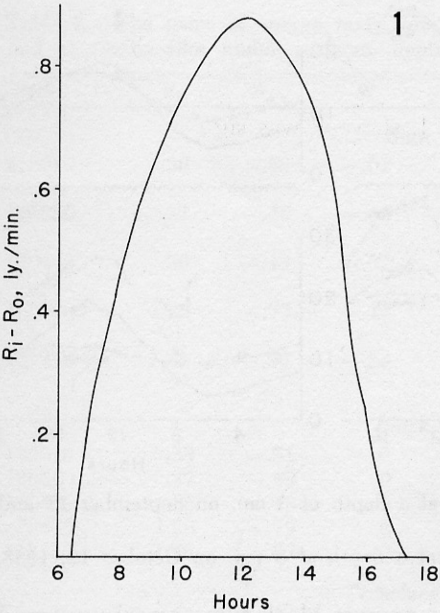
The A, energy exchanged with the atmosphere by conduction and convection, could not be estimated independently. Rather, it was estimated by difference from the energy budget. These estimates of A were compared, for reasonableness, with the vertical temperature gradients in the air. The comparison was accomplished through calculation of a coefficient of exchange

$$K_{air} = \frac{A}{\triangle T/\triangle z}$$

where the difference in temperature $\triangle T$ was taken over the $\triangle z$ from 0 to 1 cm. This coefficient of exchange is equal to the product of the virtual coefficient of conduction, the specific heat of air at constant pressure, and the density of air. The K_{air} on clear days has been estimated near 1/10 (ly./min.)/(°C./cm.) (Sutton, 1953: Table 21).

Temperatures resulting from the energy budgets were measured by 30-gauge copper-constantan thermocouples exposed at heights of 1, 3, and 9 cm. near the centers of the quadrants. Others were pressed against the surfaces of the film or soil and buried at depths of 1, 3, and 9 cm.

The observations were begun on September 11 at 7 P.M. Eastern Standard Time which was written as 111900 hours. (The first two digits indicate the day of the month; the last four indicate the time on a 24-hour clock.) They were continued until the following evening in the plots covered by black, translucent, and aluminum film. The clear



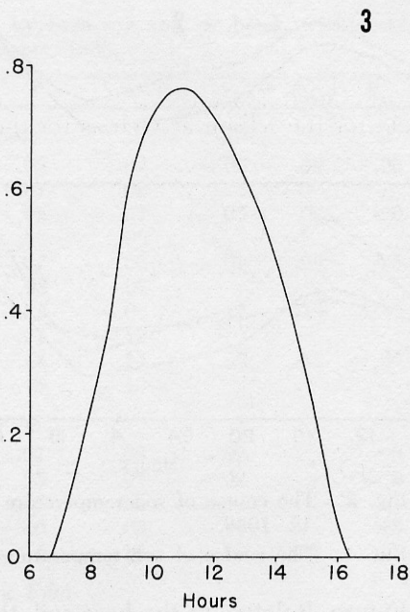


Fig. 1. Positive net radiation on September 12, 1958.
Fig. 3. Positive net radiation on October 12, 1958.

sky caused a nearly ideal course of radiation as shown in the graph of daytime net radiation, Figure 1. This curve was the basis for the estimation of evaporation at a given time from the daytime observations accumulated over 330 and 655 minutes, Table 1. The soil moisture was at or near field capacity, 24 per cent on a volume basis. Thus, observations were made during a simple and comprehensible pattern of radiation.

The disposition of energy by the four surfaces, one bare and three covered by film, is reflected in the course of temperature at a depth of 3 cm., Figure 2. The characteristics of the three film-covered plots, which were repeatedly shown on following days, are evident in the

Table 1. Evaporation in g./cm.² from the surface of soil contained in aluminum cans.

	Mulch			
Time, hours	None[*]	Black	Translucent	Aluminum
(September 1958)				
111900 to 120630	.021, .032	. . .	. . .	. . .
120630 to 121200	.104, .112	. . .	. . .	. . .
120630 to 121725	.144, .150	.037, .021	−.032, .019	.003, −.008
(October 1958)				
111635 to 120540	.059, .040	. . .	. . .	. . .
120540 to 121145	.032, .056	. . .	. . .	. . .
121145 to 121900	.024, .024	. . .	. . .	. . .
121900 to 130945	.013, .013	. . .	. . .	. . .

[*] Duplicate observations.

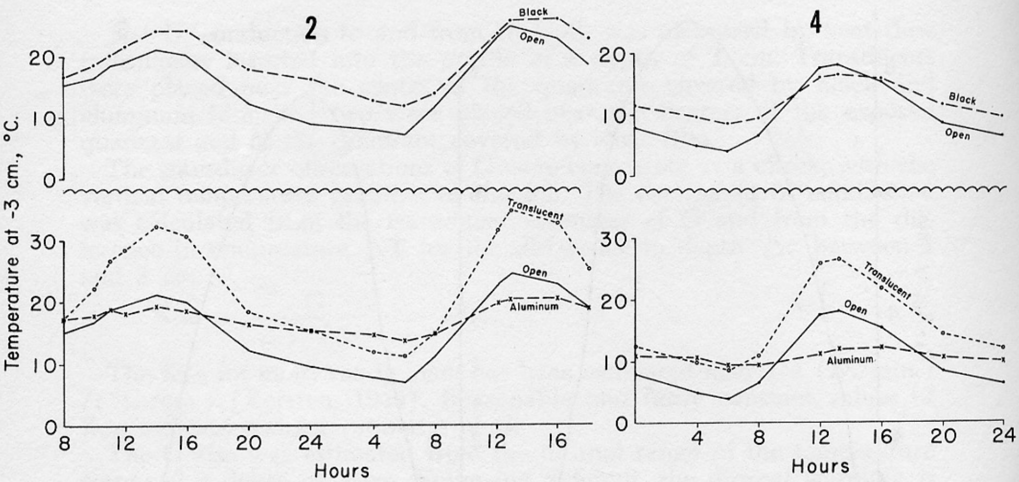


Fig. 2. The course of soil temperature at a depth of 3 cm. on September 11 and 12, 1958.

Fig. 4. The course of soil temperature at a depth of 3 cm. on October 12, 1958.

Figure. Relative to the bare soil, the opaque black film scarcely warmed the soil at all during the day, but kept it several degrees warmer at night. The translucent film, holding its deposit of water droplets beneath it, warmed the soil many degrees during the day and a few at night. The reflective aluminum film cooled the soil several degrees during the day and kept it several degrees warmer at night.

The dispositions of energy, which controlled the temperature courses, are set out in Table 2. The bare soil serves as a reference and appears at the head of the table. The incoming radiation R_i decreased through the night from 0.38 to 0.36 ly./min.; then it increased to a maximum of 1.82 at noon. The loss by outgoing radiation R_o from the bare soil decreased from -0.50 to -0.48 ly./min. during the night. This nighttime outgoing radiation equaled 93 to 96 per cent of the black-body radiation σT^4 that is equivalent to the temperature of the thermocouple pressed against the surface. Outgoing radiation increased to -0.73 and -0.90 ly./min. at 0830 and 1210 hours as the surface temperature increased and a fraction of the increasing insolation was reflected. The increasing reflection is shown in the excess of outgoing radiation above the black-body radiation: $|R_o| - \sigma T^4$ increased from 0.15 to 0.25 between 0830 and 1210 hours. (The vertical bars indicate that the value of R_o is used irrespective of sign.)

Evaporation W, as shown by loss of water from the cans of soil, Table 1, consumed only .02 ly./min. at night, but it consumed .34 ly./min. at midday.

During the night conduction G from the soil furnished the surface with .09 to .06 ly./min., the amount decreasing slightly through the night as the soil cooled. The G removed about 0.09 ly./min. from the surface at 0830 hours, 0.14 at 1210. The spatial variation of soil and instruments is shown in the 7 to 20 per cent difference between the duplicate observations shown at each time. When the spatial mean of

Table 2. The gains of energy in ly./min. by bare soil and by black, translucent, and aluminum film mulch surfaces. September 1958.

Time	R_i	R_o	W	A	G	$\lvert R_o \rvert - \sigma T^4$ *	K_{soil}	K_{air}
				Bare Soil				
112010	.38	−.50	−.02	.05	.07	−.02	.09	.06
				.07	.09			
120020	.37	−.48	−.02	.05	.07	−.03	.09	<0
				.06	.08			
120440	.36	−.48	−.02	.07	.06	−.01	.08	<0
				.08	.07			
120830	1.26	−.73	−.17	−.28	−.08	.15	.13	....
				−.21	−.10			
121210	1.82	−.90	−.34	−.44	−.14	.25	.08	.26
				−.45	−.13			
				Black Film				
112010	.38	−.51	0	.07	.06	−.02	....	<0
120020	.37	−.49	0	.05	.07	−.02	....	<0
120440	.36	−.48	0	.06	.06	−.01	....	∞
120830	1.28	−.79	0	−.46	−.03	.16		.13
121210	1.76	−.88	0	−.74	−.14	.10	.07	.11
				Translucent Film				
112010	.38	−.53	0	.04	.10	0	.11	∞
				.06	.09			
120020	.37	−.50	0	.03	.10	0	.10	<0
				.05	.08			
120440	.36	−.49	0	.04	.09	−.01	.10	<0
				.05	.07			
120830	1.25	−.75	0	−.39	−.11	.18	.14	∞
				−.43	−.07			
121210	1.81	−1.04	0	−.50	−.27	.34	.08	.17
				−.58	−.18			
				Aluminum Film				
112010	.38	−.39	0	−.02	.03	−.14	.15	.06
120020	.37	−.38	0	.01	.03	−.13	.15	<0
120440	.36	−.38	0	−.01	.03	−.13	.12	0
120830	1.27	−.81	0	−.44	−.03	.23	.40	∞
121210	1.77	−1.46	0	−.26	−.05	.82	.11	.14

* The difference between the absolute magnitude of the outgoing radiation and the black-body radiation equivalent to the surface temperature.

G for a given time is compared to the corresponding temperature gradient between 1 and 3 cm., a reasonably constant coefficient of conduction K_{soil} results, attesting to the usefulness of the observations of G. These K_{soil} results are tabulated in Table 2. Our K_{soil} results are about half those given by Kersten (1949) for a sandy loam, indicating that, although our observations of G are consistent within themselves, their absolute values may be low.

A further estimate of G arises from the diurnal range from 7 to 24° C. in the soil temperature, Figure 2. Multiplying the range by 3.4 ly./degree provides an estimate of 58 ly. for the heat stored during the morning. Heat was stored from about 0600 to 1300 hours or a total of 420 minutes;

thus, the estimate of G based upon the range requires an average storage of 0.14 ly./min. This also suggests that, although our observations with the transducers are consistent within themselves, their absolute values may be low.

The exchange of energy A by conduction and convection with the air varied from a small gain from the air at night to the much larger 0.45 ly./min. loss at midday.

The reality of our estimate of A is tested by comparison with the aerial temperature gradient through a calculation of K_{air}, a coefficient of conduction. The account A must be estimated from the difference in the other four accounts and is affected by errors in them. The greatest difficulty exists at night when the absolute amounts are small, and the smallest inexactitudes cause large relative errors. Hence, the errors in the signs of K_{air} are not surprising; they arise from simultaneous observations of small, nighttime gains through A and soil or film temperatures warmer than the air. On the other hand, the K_{air} of 0.26 near noon is reasonable and occurs when the absolute amounts of energy are largest. These characteristics of K_{air} and, hence, A also will be seen in the budgets for the films.

The course of temperature and the disposition of energy by the mulches can now be compared with the reference or bare soil, Table 2. The nighttime temperature 3 cm. beneath the black film fell less than the temperature beneath an exposed surface, Figure 2. The film conserved a little energy by stopping evaporation, W, Table 2. The film did not lose significantly different amounts by radiation R_o or exchange A than did the bare soil. The surface's gain and the soil's loss G was measured by the transducers and perhaps was less from the covered soil than from the bare soil. The magnitude of all these differences is small and one cannot be certain of the details. However, the larger view is clear: the film lost a little less energy through R_o, A, and W, while an insulating air layer beneath the black film prevented a large loss G from the soil and kept the soil temperatures higher beneath the film than beneath a bare surface.

During the day the soil covered by the black film remained warmer than the bare soil. But the covered soil warmed more slowly and the difference between covered and exposed soil decreased through the morning, Figure 2. This failure is paradoxical for two reasons. First, the film saved 0.17 ly./min. at 0830 and 0.34 at 1210 which the bare soil consumed in evaporation. Second, the black film reflected less energy at midday than did the bare soil, causing $|R_o| - \sigma T^4$ to be 0.15 ly./min. less for the film than for the bare soil. Why did this conserved energy not produce a greater rise in soil temperatures?

The opaque film transmitted no insolation, instead converting it into sensible heat and causing the film to become 14° C. hotter than the bare soil. This increased the thermal radiation from the film, compensating for the decreased reflection and making the outgoing radiation equal from soil and film. The increased temperature of the film increased the loss A to the air, roughly compensating for the energy saved when the film stopped evaporation. The air layer beneath the film, with its low conductivity, prevented the high temperature of the film from causing an increased storage of heat G in the soil. Slater and Broach (1958) surmised these processes from temperature observations alone.

Thus, the energy which the film conserved through decreased reflection and evaporation was not translated into increased soil temperature; rather it was lost through increased long-wave, thermal radiation, and increased transfer to the air above.

The effect of the black film upon soil temperature can be summarized by converting the diurnal range of the soil temperature into an estimate of heat storage in the soil. The temperature at 3 cm. depth increased from 11.5 to 25.5° C. This corresponds to a storage of 48 ly. and is less than the 58 ly. of the bare soil. Thus, at night the film conserved a bit of energy by stopping evaporation and—since the layer of air beneath the film acted as an insulator—heat was conserved in the soil. Then, during the day, the energy saved through lack of evaporation and less reflection produced a high film temperature, high radiation R_0 and high exchange A, while the layer of air beneath prevented a large storage of energy in the soil. Consequently, the temperature beneath the black film was always slightly warmer and fluctuated less from night to day than the temperature beneath a bare surface.

This outcome has been attributed to the air space between soil and film, and if it were absent through the perfect attachment of film to soil, midday soil temperature and diurnal range would be increased, not decreased by a black film. This has been demonstrated over the years in countless coatings of the soil with carbon black. Recently, Slater and Broach (1958) saw the temperature of soil increase as the covering black film was lowered from a height of 2.5 cm. to a height of 0. But perfect contact is not found in a field mulched with black plastic; in the field this film will exchange large amounts of energy with the air and cause relatively small changes in soil temperature, as we noted in the preceding paragraphs.

Now we turn to the course of temperature beneath the translucent film and the deposit of water droplets supported beneath it. The warm soil beneath the clear film cooled more rapidly at night but still remained warmer at dawn than the relatively cool exposed soil, Figure 2. The film conserved a little energy by stopping evaporation W, Table 2. Despite the greater warmth of the covered soil, it lost little more by outgoing radiation R_0 than the exposed soil; this was caused by the interposition of the layer of water droplets on the film: they were opaque to the soil's thermal radiation, absorbed it, and returned a portion to the soil. The layer of air beneath the film prevented a rapid loss of heat to the air above and, hence, the exchange A from the warm, covered soil was no greater than from the cooler, bare soil. The surface's gain and the soil's loss G was measured by two transducers and was clearly greater than the loss from the exposed soil.

During the day, the temperature beneath the film rose still higher than beneath the exposed surface. The film saved 0.17 ly./min. at 0830 hours and 0.34 at 1210 which the bare soil consumed in evaporation. Some of this advantage was lost by reflection and increased thermal radiation R_0 and some by increased exchange A with the air above. Nevertheless, energy still remained for a greater storage G in the covered than in the bare soil, a fact clearly shown by the transducer observations of G at 1210 hours.

The translucent film, unlike the opaque black one, transmitted much insolation which was then absorbed and converted to sensible heat at the sheltered soil surface. The increased warmth of the soil caused an increased thermal radiation R_o and potentiality for exchange A, but these were nullified by the absorption of thermal radiation in the water droplets on the film and by the insulation of the layer of air beneath the film. Thus, some of the energy which the translucent film conserved through decreased evaporation was translated into hotter soil temperatures.

The effect of the translucent film upon soil temperature can be verified and summarized by transforming the diurnal range of the soil temperature into an estimate of heat storage in the soil. The temperature 3 cm. below the film increased from 11.0 to 34.5° C. This corresponds to a storage of 80 ly. and is more than the storage in soil exposed or covered by black plastic. Thus, the film and the water droplets beneath it conserve energy by stopping evaporation and retarding the loss of thermal radiation from the warm soil, while they permit the transmission to the soil of any short-wave insolation. Both Slater and Broach (1958) and Army and Hudspeth (1960) have inferred from temperature observations that the translucent plastic mulch operates as a greenhouse.

The great reflectivity and low emissivity of the aluminum film produced a temperature course remarkably different from the courses beneath the opaque black or translucent natural polyethylene films. The nighttime temperature 3 cm. beneath the aluminum film fell much less than the temperature beneath an exposed surface or one covered with the other films, Figure 2. The aluminum conserved a little energy by stopping evaporation W, Table 2. And despite the warmth of the covered soil, the foil conserved much energy by emitting only four-fifths as great R_o as the bare soil; in other words, from aluminum the outgoing R_o is fully 0.13 ly./min. less than the black-body radiation σT^4 corresponding to the temperature of the film. The aluminum film was a bit warmer than the other surfaces and gained slightly less energy from the atmosphere than the bare soil or other films. Nevertheless, the conservation in R_o and W was much greater than the lack of gain from A; hence, the loss of energy G from the soil was no more than half the losses to the exposed surface or the other films.

During the day the temperature beneath aluminum rose much less than beneath the exposed surface. The metal saved 0.17 ly./min. at 0830 hours and 0.34 at 1210 which the bare soil consumed in evaporation W. But through increased reflection, it lost as much as twice as many units of energy through outgoing radiation R_o, eliminating 0.08 to 0.57 ly./min. from the foil system that was not lost from the bare soil through the same path. The A, exchange with the air, is different when estimated by subtraction in Table 2. However, this is difficult to believe because the two surfaces have approximately the same temperature. We believe instead that the two had about the same coefficients of exchange and the same exchange A. (The source of the inaccuracy may be an underestimation of R_o at a low solar angle, 0830 hours, and an overestimation at a high solar angle, 1210, above the reflective foil.) Thus, through reflection and despite lack of evaporation, the aluminum-covered soil gained less energy than the exposed soil, a lack shown in the low storage G measured by the transducers in the soil.

The effect of the aluminum film upon soil temperature can be summarized by transforming the diurnal range of the soil temperature into an estimate of heat storage in the soil. The temperature 3 cm. below the film increased from 13.8 to 20° C. This corresponds to a storage of 21 ly. and is less than the storage in soil exposed or covered by the other films. Thus the foil conserves energy by stopping evaporation and emitting little, and it absorbs little energy by reflecting much.

The foregoing observations and conclusions were verified on October 12, 1958. The films had been in place for another month and better represented the practical film that would be left in the field for an entire season. A cold front passed on the evening of October 11 and was followed by clear continental polar air and a brisk wind. The course of radiation was nearly ideal as shown in the graph of daytime net radiation,

Table 3. The gains of energy in ly./min. by bare soil and by black, translucent, and aluminum film mulch surfaces. October 1958.

Time	R_i	R_o	W	A	G	$\lvert R_o \rvert - \sigma T^4$	K_{soil}	K_{air}
				Bare Soil				
120020	.36	—.48	—.04	.12	.04	—.02	.31	.17
				.11	.05			
120530	.31	—.45	—.04	.10	.08	—.01	.09	.10
				.12	.06			
121000	1.36	—.78	—.12	—.37	—.10	.20	.10	.09
				—.34	—.13			
121210	1.49	—.85	—.10	—.41	—.13	.23	.10	.07
				—.40	—.15			
121850	.38	—.48	—.01	.04	.07	—.20	.08	.08
				.05	.06			
				Black Film				
120020	.36	—.48	0	.07	.04	—.02	.45	∞
120530	.31	—.45	0	.08	.06	—.02	.07	∞
121000	1.40	—.64	0	—.69	—.06	.04	.06	.12
121210	1.51	—.79	0	—.65	—.07	.13	.05	.06
121850	.38	—.47	0	.04	.05	—.03	.12	.13
				Translucent Film				
120020	.36	—.50	0	.06	.07	0	.20	.09
				.07	.07			
120530	.31	—.46	0	.06	.09	—.01	.09	.06
				.05	.10			
121000	1.36	—.77	0	—.40	—.19	.19	.10	.10
				—.48	—.12			
121210	1.42	—.78	0	—.50	—.14	.14	.10	.05
				—.43	—.22			
121850	.38	—.51	0	.04	.09	.01	.12	.04
				.02	.10			
				Aluminum Film				
120020	.37	—.39	0	0	.03	—.12	.12	0
120530	.31	—.33	0	—.02	.04	—.15	.08	.01
121000	1.34	—.92	0	—.41	0	.36	<0	.34
121210	1.50	—1.10	0	—.38	—.02	.51	.19	.10
121850	.38	—.39	0	—.01	.02	—.12	.07	.01

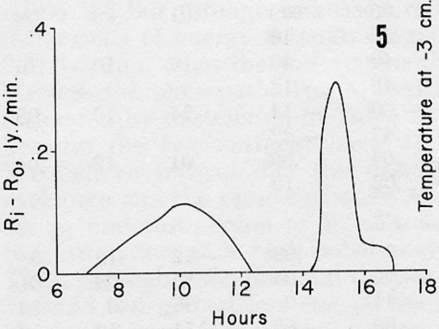
Figure 3. The soil was at or near field capacity. The evaporation from the surface of cans of soil is shown in Table 1. The courses of soil temperature beneath the films are shown in Figure 4, and the dispositions of energy by the four surfaces are tabulated in Table 3.

The salient features of the three films were verified. Beneath the black film the soil temperature changed less than beneath an exposed surface: at night the soil was warmer beneath the film, but it was warmed slowly by the sun. The cause of the slow warming beneath the black film is evident in Table 3 as it was in Table 2: a hot surface caused a high loss of energy A by exchange with the air. Beneath the translucent film the soil temperature was higher and changed more than beneath the other surfaces. The cause of the warmth of the soil again is evident in the energy budget, Table 3: the increase in outgoing radiation R_o and exchange with the air A was negligible despite higher soil temperatures because of the sheltering but translucent film. Beneath the aluminum film the soil temperature changed less but averaged about the same as that beneath the bare surface. The sources of the temperate climate beneath the aluminum are evident once again in Table 3: the low emissivity and high reflectivity of the metal caused a low outgoing radiation R_o at night and a high one in the daytime. The storage in soil G changed as expected, and the factors mentioned above were the critical ones that gave each film its characteristic.

Cloudy skies must cause the films to behave differently; before we leave these particular mulches, we shall observe what happened on a day with overcast skies and intermittent rain, October 13, 1958. Following clear October 12, the polar air on the west side of the high flowed from the south, and clouds appeared. Occasional sprinkles of rain fell, but the exposed soil surface was mostly dry; just beneath, it was at field capacity. The low net radiation is graphed in Figure 5. The evaporation during the night was slight, Table 1, and during the day was not measured due to the light rain.

The courses of the soil temperature beneath the films are shown in

5



6

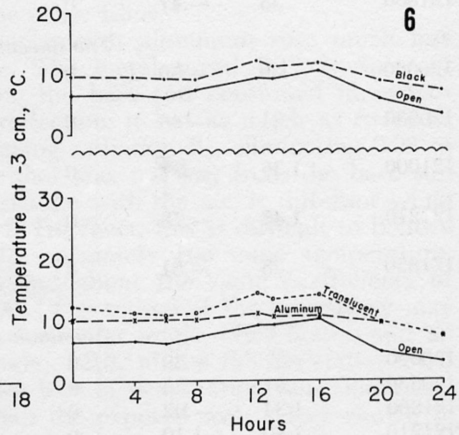


Fig. 5. Positive net radiation on October 13, 1958.

Fig. 6. The course of soil temperature at a depth of 3 cm. on October 13, 1958.

Table 4. The gains of energy in ly./min. by bare soil and by black, translucent, and aluminum film mulch surfaces. October 1958.

Time	R_i	R_o	W	A	G	$\|R_o\| - \sigma T^4$	K_{soil}	K_{air}
				Bare Soil				
130940	.63	−.54	−.01	−.06	−.01	.03	.05	.05
				−.06	−.01			
131120	.64	−.56	0	−.09	0	.04	....	.24
				−.08	0			
				Black Film				
130940	.63	−.54	0	−.08	−.01	.01	.03	.02
131120	.66	−.57	0	−.09	0	.04	....	.04
				Translucent Film				
130940	.62	−.56	0	−.06	−.01	.03	.05	.05
				−.06	0			
131120	.63	−.58	0	−.05	0	.05	....	.05
				−.05	0			
				Aluminum Film				
130940	.62	−.58	0	−.03	0	.06	....	.06
131120	.65	−.60	0	−.04	0	.08	....	.20

Figure 6 and the dispositions of energy by the four surfaces are tabulated in Table 4. The increased incoming radiation from the cloudy nighttime sky and the decreased input of energy from the sun led to a corresponding decrease in the diurnal temperature change and a smaller divergence among the plots. Nevertheless, the covered plots remained warmer than the bare one. And the warmth of the black film itself and the increased outgoing radiation from the aluminum were evident, but to a lesser degree than on a sunny day. On this cloudy day, the translucent film was able to maintain a higher temperature, but it did not succeed in storing more energy in the soil than the bare surface; evidently this was caused by the higher outgoing radiation R_o from the warm, covered plot. Thus, the films can change the distribution of energy and the soil temperatures on cloudy days, although the effects are smaller than the dramatic changes seen on clear days. Now we turn to other, more familiar soil coverings.

Paper, hay, and black film

The following spring the same plots were prepared. This time one was covered with hay to a depth of 6 cm., one was covered with tan kraft paper, one was again covered with the black plastic film, and one remained bare. The accounts of the energy budget and the temperatures were observed as before.

The observations were begun on June 10. The observations of a clear day, June 11, are summarized: net radiation in Figure 7, temperature courses in Figure 8, evaporation in Table 5 and energy budgets in Table 6. The can of soil beneath the black film lost more water than previously; this was attributed to a nearby slit in the film, and evaporation W was set equal to zero in the budgets. On the other hand, the soil be-

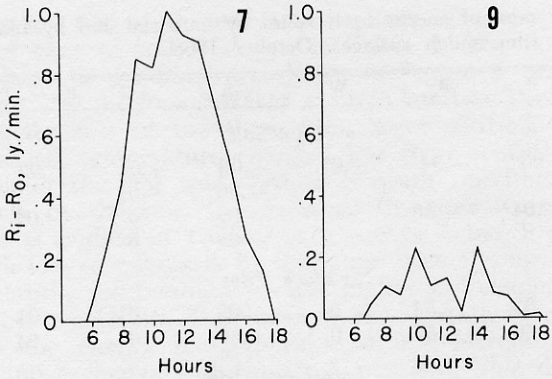


Fig. 7. Positive net radiation on June 11, 1959.
Fig. 9. Positive net radiation on June 12, 1959.

neath the paper and the hay dried noticeably during the ensuing days, and the estimates from the cans were used to calculate W in the budgets for these two coverings.

The courses of temperature beneath the bare surface and the black plastic film repeated their familiar patterns: beneath the black film the soil warmed less and cooled less, maintaining a higher mean temperature than the soil beneath the bare surface. The hot black film and its high loss of energy A to the daytime air are once again revealed in the energy budget.

The paper bears some resemblance to the aluminum film. Both reflected large quantities of radiation, increasing the daytime loss through R_o. But unlike the aluminum, the paper did not emit less radiation at night. The exchange A with the air was not materially affected and, although evaporation W was decreased, the saving was not large. Hence, the maximum soil temperature beneath paper was decreased, as beneath

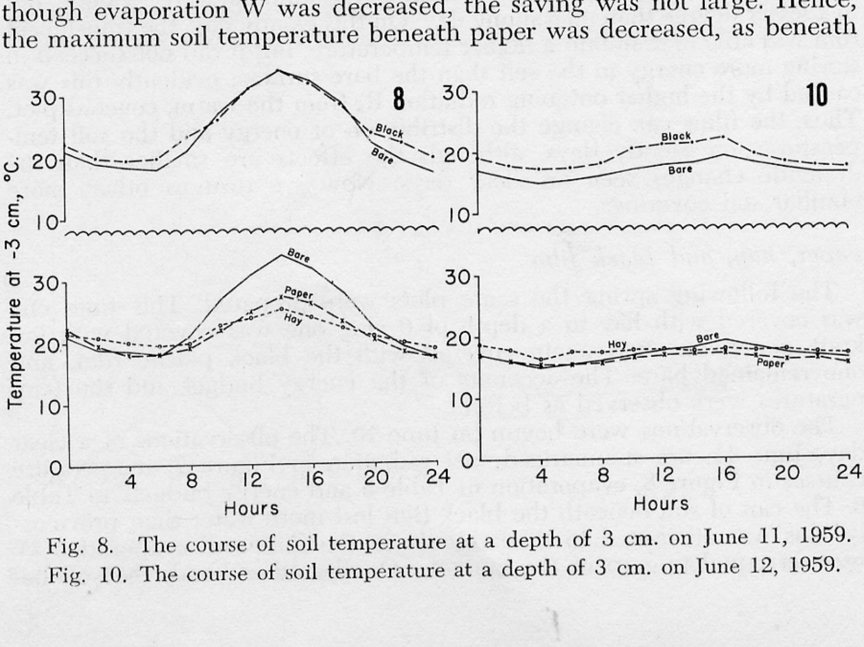


Fig. 8. The course of soil temperature at a depth of 3 cm. on June 11, 1959.
Fig. 10. The course of soil temperature at a depth of 3 cm. on June 12, 1959.

Table 5. Evaporation in g./cm.^{2} from the surface of soil contained in aluminum cans. June 1959.

Time, hours	Mulch			
	None*	Black	Paper	Straw
111041 to 111600	.128, .136	.045	.045	.059
111600 to 121100	.045, .051	.018	.056	.053
121100 to 121430	.016, .008	.013	.005	.016

* Duplicate observations.

aluminum, but the minimum temperature was not increased, unlike aluminum.

The hay mulch presented still another mechanism. The outgoing radiation was essentially the same above hay and bare soil. Some conservation of energy was realized through a small diminution in evaporation W. However, the major change was in the exchange A with the air. During midday, the hay on the surface became hot because the downward movement of heat was retarded by the insulating air and organic matter of the hay mulch; hence, the loss A was increased by fully 0.2 ly./min. This midday loss exceeded the savings in the W account and resulted in a greater net loss from the hay than from the bare soil. Consequently, the storage G of energy in the soil beneath the hay was only half the storage in the bare soil.

At night the hay reversed the process: the hay at the surface became about 2° C. colder than the bare soil and the gain of energy A from the air was increased, the loss by radiation R_0 was decreased. Consequently, the loss of energy G from the soil was less beneath the insulating hay than from the bare soil. This decreased loss, together with the decreased daytime gain, produced a decreased maximum soil temperature, like paper, and an increased minimum, unlike paper. At the same time, this mechanism of insulation gave the surface of the hay its well-known intemperate nature, causing seedlings to scald at midday and freeze at night.

Cloudy skies undoubtedly cause these mulches to behave differently, and we shall continue our examination of them with the observations of a day with overcast sky, June 12. Following clear June 11, clouds appeared at dawn on the 12th, darkening the entire sky shortly afterwards. The small quantity of net radiation is graphed in Figure 9.

The course of soil temperature, pictured in Figure 10, exhibits the small diurnal range expected from the small input of solar energy. The soil sheltered by the black film retained its usual warmth, the soil shielded by paper failed to follow even the slight warming of the bare soil, and the soil insulated by hay remained warmer than the bare soil except at the peak of the warming trend. Some of the causes, which were apparent on a sunny day, are still distinguishable on the cloudy day; the warmth of the black film and the insulation of the layer of air beneath; the reflection and high loss R_0 from the paper, Table 7. The surface of the hay became relatively warm on the cloudy day, as it did on the clear day. The consequent increase in outgoing radiation R_0 was evident, but the increase in exchange A was not seen. In any event these small daytime losses and nighttime gains relative to the bare soil caused a

Table 6. The gains of energy in ly./min. by bare soil and by black film, paper, and hay mulch surfaces. June 1959.

Time	Mulch	R_i	R_o	W	A	G	$\|R_o\| - \sigma T^4$	K_{soil}	K_{air}
110940	None	1.53	−.94	−.19	−.27	−.13	.22	.06	.04
					−.29	−.11			
1100		2.06	−1.14	−.28	−.50	−.13	.38	.06	.05
					−.53	−.11			
1325		1.83	−1.07	−.24	−.41	−.11	.27	.06	.04
					−.42	−.10			
1500		1.54	−.99	−.18	−.29	−.08	.23	.04	.03
					−.31	−.06			
1735		.76	−.69	−.05	−.06	.04	.05	.14	.01
					.07	.05			
2000		.42	−.55	−.02	.07	.08	−.03	.05	<0
					.07	.08			
2355		.42	−.52	−.02	.06	.06	−.01	.10	<0
					.06	.06			
120350		.49	−.52	−.02	0	.05	0	.10	0
					0	.05			
110940	Black	1.52	−.89	0	−.53	−.10	.04	.04	.04
1100		2.04	−1.02	0	−.90	−.12	.13	.04	.05
					−.92	−.10			
1325		1.84	−1.05	0	−.68	−.11	.21	.04	.02
					−.68	−.11			
1500		1.52	−.94	0	−.52	−.06	.18	.04	.08
					−.52	−.06			
1735		.75	−.70	0	−.09	−.04	.03	.34	.01
					−.08	−.03			
2000		.42	−.54	0	.02	.10	−.02	.06	<0
					.04	.08			
2355		.42	−.52	0	.03	.07	−.02	.13	∞
					.04	.06			
120350		.49	−.53	0	−.02	.06	−.02	.16	<0
					−.01	.05			
110940	Paper	1.52	1.09	−.04	−.34	−.05	.37	.04	.07
1100		2.05	−1.43	−.06	−.50	−.06	.65	.04	.05
1325		1.84	−1.31	−.05	−.42	−.06	.57	.04	.06
1500		1.54	−1.21	−.03	−.26	−.04	.48	.04	.04
1735		.76	−.77	−.02	−.01	.04	.14	<0	0
2000		.42	−.52	−.02	.06	.06	−.06	∞	<0
2355		.42	−.50	−.02	.05	.05	−.03	.40	<0
120350		.49	−.52	−.02	.01	.04	−.03	.40	0
110940	Hay	1.53	−.97	−.08	−.44	−.04	.18	.04	.04
1100		2.06	−1.19	−.12	−.70	−.05	.35	.04	.05
1325		1.79	−1.01	−.11	−.63	−.04	.20	.04	.05
1500		1.52	−.98	−.08	−.44	−.02	.24	.04	.05
1735		.77	−.69	−.02	−.09	.03	.08	.30	.03
2000		.42	−.53	−.02	.09	.04	−.06	∞	.36
2355		.42	−.50	−.02	.07	.03	−.03	.24	.70
120350		.49	−.51	−.02	.01	.03	−.03	.24	∞

Table 7. The gains of energy in ly./min. by bare soil and by black film, paper, and hay mulch surfaces. June 1959.

Time	Mulch	R_i	R_o	W	A	G	$\|R_o\| - \sigma T^4$	K_{soil}	K_{air}
120600	None	.55	−.56	−.02	0	.03	.02	<0	0
					0	.03			
0920		.74	−.62	−.04	−.07	−.01	.04	.03	.06
					−.08	0			
1130		.76	−.58	−.03	−.15	0	−.01	0	.10
					−.15	0			
1520		.70	−.61	−.03	−.06	0	.01	0	.04
					−.06	0			
2000		.55	−.57	−.02	.02	.02	0	∞	∞
					.02	.02			
120600	Black	.55	−.55	0	−.03	.03	0	∞	.06
						.03			
0920		.74	−.62	0	−.09	−.01	.03	<0	.06
					−.09	−.01			
1130		.76	−.60	0	−.16	0	−.01	0	.08
					−.15	−.01			
1520		.71	−.63	0	−.08	0	.03	0	.08
					−.07	−.01			
2000		.55	−.58	0	0	.03	.01	<0	∞
					.01	.02			
120600	Paper	.55	−.56	−.02	0	.03	0	.18	0
0920		.74	−.65	−.03	−.07	.01	.08	.02	.04
1130		.76	−.64	−.02	−.11	.01	.05	<0	.08
1520		.70	−.66	−.02	−.02	0	.06	0	.01
2000		.55	−.56	−.02	.02	.01	0	<0	<0
120600	Hay	.55	−.57	−.02	.02	.02	.03	∞	.06
0920		.74	−.64	−.03	−.07	0	.05	0	.03
1130		.76	−.61	−.04	−.12	.01	.02	<0	.18
1520		.70	−.62	−.04	−.04	0	.02	0	.02
2000		.55	−.56	−.02	.02	.01	.01	<0	<0

smaller daytime storage and nighttime loss G of energy from the soil beneath hay.

This completes our examination of the causes of the warm and equable climate beneath black film, the warmer and variable climate beneath translucent film, the temperate and steady climate beneath aluminum film and hay, and the cool and equable climate beneath paper. We extend our observations now to the outcome of these causes under the vagaries of weather.

Soil Temperatures in a Variety of Weather

The function of several mulches has been observed under clear and cloudy skies. But we still want a demonstration of the changes in soil temperature produced during an extended period. Therefore, after nature had integrated the sum of several days, the result was read as the depth to which once-frozen soil had thawed, or the result was read as the change in temperature far beneath the surface. Finally, the diurnal ranges of soil temperature were compared over several days.

Thawing of frozen soil

In the fall, plots of Cheshire fine sandy loam were covered with black, translucent, and aluminum film, a hay mulch, or left bare. The winter was cold and the snowfall light. Then in early March the daytime temperatures rose above freezing and the nighttime temperatures dropped to only 16 to 38° F. or −11 to 3° C. with an average of 26° F. or −3° C. Snow fell on March 10, 11, 12, and 13 and rain on March 15 and 16. On March 17 we measured the depth of thawed soil at three locations in each of the four replicates.

The soil was thawed to the following mean depths:

Bare soil	Black film	Translucent film	Aluminum film	Hay mulch
19 cm.	18	35	13	11
7½ inches	7	14	5⅛	4¼

The standard error of a difference between two means is 2 cm. The black film had little ability to warm the soil, and this was reflected in its inability to increase thawing. The translucent film had great ability to warm the soil, and this was verified in a doubling of the depth of thawing. Finally, the aluminum film and hay mulch had both retarded the warming of soil, and this was reflected in significant decreases in the depth of thawing. Thus, the physical reasoning of the preceding chapters and observations of single days are a useful basis of prediction for longer periods, even the seasonal warming of the soil.

Soil temperatures far beneath the surface

On June 14 through 23, 1958, the sun shone more than 10 hours on three days, 5 to 10 hours on two and less than 5 hours on five, providing an assortment of weather. Then, on June 24, pits were dug in the plots and thermometers inserted into the soil profile with the following results:

	Bare	Black	Translucent	Aluminum
2.5 cm.	24.7° C.	25.0	28.3	22.8
15	21.1	20.0	23.3	20.0
30	19.4	18.3	20.0	18.3
61	17.2	16.7	18.3	16.1

Clearly, the modification of soil climate possible to mulches is neither fleeting nor superficial but continues through a variety of weather until it is felt throughout a volume of soil as great as that occupied by many roots.

Diurnal mean and range of soil temperatures

The mean temperature of the soil at a depth of 3 cm. indicates the climate created for roots; it also shows the temperature required to balance the accounts of the energy budget. The soil was observed 3 cm. beneath black, translucent, and aluminum films, and a bare surface during 12 autumnal days. The weather varied from clear to overcast, Table 8.

The black film consistently increased the mean temperature, largely through increasing the minimum temperature and decreasing the loss

Table 8. The diurnal mean and range of temperatures 3 cm. below films expressed as the difference from a bare soil.

Date	Sky	Mean less mean beneath bare			Range less range beneath bare		
		Black	Translucent	Aluminum	Black	Translucent	Aluminum
Sept. 11	Partly cloudy	5.0°C.	8.7	2.1	−3.9°C.	5.0	−8.2
12	Clear	2.8	7.2	1.2	−3.7	6.1	−10.8
27	Overcast	0.2	0.6	−0.5	−1.5	−0.8	−2.0
Oct. 1	Overcast	0.6	2.0	−0.2	−0.9	−0.4	−2.4
2	Clear	1.2	5.7	1.2	−4.9	5.4	−7.5
3	Mostly cloudy	2.0	5.4	1.9	−3.5	2.5	−6.2
4	Partly cloudy	1.2	3.9	0.8	−2.6	0.2	−4.5
5	Partly cloudy	1.0	2.8	1.4	−1.3	2.0	−2.7
6	Clear	1.8	4.2	1.8	−4.3	1.2	−6.0
11	Clear	2.2	7.2	1.5	−6.1	4.1	−10.4
12	Clear	1.6	6.6	−0.3	−6.5	3.9	−11.1
13	Overcast	2.8	4.5	2.5	−0.9	−0.6	−3.0

and gain of energy to and from the sky and air. The translucent film was even more effective in increasing the mean temperature; on most days it brought this about by increasing the gain of energy, but it brought it about on overcast days by decreasing the loss, thus, behaving in the same way as the black film. The aluminum film generally increased the mean temperature slightly; this was entirely due to an increase in the minimum greater than the decrease in the maximum, a logical outcome of decreased emissivity and increased reflectivity. Stated in another way, the black film moderates the diurnal swing of temperature, the translucent film magnifies it, and the aluminum film minimizes it.

Growth as a Function of the Transmission of Radiation Through Mulch

Two extremes of transmission have been encountered in translucent and black polyethylene film: the hot midday temperature beneath translucent film has been attributed to its transmission; and the temperate midday temperature beneath black film has been attributed to its absorption of insolation. From this we concluded that intermediate transmission would give intermediate warming of the soil, and then set out to test the conclusion.

Thirty-six waxed paper cups, 7 cm. high and 11 cm. in diameter, were half filled with moist sand and placed upon a greenhouse bench. Six were covered with each of four polyethylene films, six with a translucent film over a black film, and six were left uncovered. At 1300 hours on clear November 19, 1959, the temperature of the sand was measured at a depth of 1 cm. The proportion of the insolation transmitted was estimated by multiplying the percentage transmission at each wavelength from 350 to 1400 millimicrons by the intensity of insolation at that wavelength (Moon, 1940) and then adding the products and dividing by the sum of the intensities. The midday temperatures, averaged for six replicates, and the transmitted proportions of radiation can be seen in Table 9.

In the autumn of 1959, three of the films were compared in the field

Table 9. Transmission of insolation, 350 to 1400 millimicrons, and soil temperatures beneath plastic films and hay. Clear sky, midday.

Mulch	None	Trans-lucent	Green A	Green B	Black	Translucent over black	Hay
Transmission	100%	80	63	40	0	0	0
Temperature, cup	27.0°C.	31.1	29.7	29.0	27.7	28.8	....
Temperature, field	30.4	36.8	35.2	....	32.6	....	26.0

to bare soil and hay mulch. The coverings were applied in a Latin square. Over winter, the hay had settled to a depth of about 2 cm. At 1300 hours on clear May 27, the temperature of the moist soil was measured by a vertical thermometer whose bulb extended from 2 to 3 cm. Once again the warming of the soil beneath a film increased as the transmission of insolation increased, Table 9.

Unfortunately, the desirable warming of the soil caused by the transmission of radiation is accompanied by undesirable weed growth. Two means of separating the desirable from the undesirable are suggested by the preceding observations. The first is exemplified by the translucent film over the black. Insolation is transmitted to the black film as usual, and it becomes hot. Where the exposed black film exchanged large quantities of heat with the turbulent air above, Table 2, the covered black film cannot; more energy must be conducted from the covered film and into the soil. Thus, both warming and weed control can be achieved by absorbing the insolation upon an opaque film that lies beyond the turbulent atmosphere.

Alternatively, weeds might be killed by excluding sufficient light of critical wavelengths, while permitting much insolation of other wavelengths to reach and warm the soil. The green film permits considerable penetration and warming, Table 9. It has essentially the same absorption spectrum as chlorophyll. Unfortunately, at least some weeds grew in the green light beneath. For example, seeds of rye grass germinated and grew in the cups of the preceding experiment.

The field experiment, begun in the autumn of 1959, was more encouraging. A superficial examination in March 1960 was discouraging because grass had begun to grow beneath both green and translucent films. Then in early May, the weeds beneath the translucent film had grown until they lifted the film to half the height of the strawberries that grew in the plots; at this time the weeds were removed from these plots. By the end of May the weeds beneath the translucent covering had again lifted the film, while those beneath the green had grown little. On May 26, the weeds upon 930 cm.^{2} of each of the five treatments and five replicates were counted and harvested, Table 10.

Different species predominated beneath the different films. Their size and number also varied. The hot and humid climate beneath the translucent film encouraged many large crab grass plants while discouraging rye grass. The green film encouraged many rye grass plants; but they, like others growing in the green light, were slender and grew upon tenuous roots. Thus, a green film seems a practical means of warming the soil, conserving soil moisture, and controlling weeds.

Another means of killing weeds while admitting some radiation is suggested by the stimulation of lettuce seed germination by wave-

Table 10. The mean number and dry weight of the plants growing upon five areas of 930 cm.². May 27, 1960.

	Mulch				
	None	Translucent*	Green A	Hay	Black
	Geometric mean of number of plants				
Crab grass	1	21	4	0	0
Other grass, mostly rye grass	36	9	70	4	0
Broadleaved plants	11	24	4	3	0
	Arithmetic mean of dry weights†				
All shoots, g.	2.0	3.7	1.1	0.2	0

* Weeds had been removed from beneath translucent film on May 10. No weeds had been removed from other plots.

† Least significant difference, P = .05, is 1.7 g.

lengths of 600 to 700 millimicrons and its suppression by wavelengths of 700 to 800 (Hendricks and Borthwick, 1959). Independently, Dr. Sterling Hendricks and Conrad Yocum have suggested to the authors the use of blue and red films together, a combination that would exclude the stimulatory and admit the inhibitory wavelengths.

Seeds of lettuce were placed on moist paper in petri dishes, following the practice of Yocum. In our experiment, the seed of rye grass was added. Then one dish was covered by both red and blue cellophane, while another dish remained bare. The two films transmitted 3 per cent of the light at 350, less than 2 per cent at 375 to 675, 28 per cent at 700, and over 80 per cent at 750 to 1400 millimicrons.

The lettuce seed germinated rapidly in the uncovered and failed in the film-covered dish, corresponding to the results of Yocum and demonstrating the suitability of the films. Unfortunately, the rye grass germinated more rapidly in the infra-red light beneath the films than it did in the visible light in the bare dishes. Thus, the red plus blue films would not prevent the germination of all weeds, only those with a germination-control mechanism like that of lettuce. Since the green film transmits more warming radiation than the red and blue and since the combination did not completely suppress weeds, the green seems the more practical device for warmth and a limitation upon weeds. It also conserves soil moisture, a subject which we shall discuss next.

Evaporation

Soil moisture is lost to the air both from the surface of the soil and from plants. We saw in the preceding sections how the loss from the surface of the soil dwindles when a plastic film is laid. We shall discuss the change in total consumption of soil moisture that follows this disappearance of one loss and then turn to the less obvious effect of mulches upon the second loss, transpiration.

The evaporation from a bare soil depends upon shelter from sun and wind and upon frequency of rain. When the soil was kept fallow for 10 years in a lysimeter at the Windsor Laboratory of The Connecticut Agricultural Experiment Station, evaporation consumed about 12 of the 17 inches of rain that fell during June through September (Morgan *et al.*, 1942). Evidently an important saving of water could be realized where the soil is bare and where frequent rainfall is quickly drained beneath a film and away from the drying sun and wind. This almost describes a mulched field of widely-spaced strawberries or of annuals in the spring before they have grown and shaded the ground.

Later when plants shade the soil, the evaporation from the soil is slight, and only a slight saving follows its covering. The conservation of water by mulching decreases as the season progresses.

These interesting possibilities have inspired a current series of studies in the conservation of soil moisture by plastic mulch, beginning with the report of Russell and Danielson (1956).

During dry 1957, we observed the increased moisture available to tobacco roots growing beneath plastic. Because plowsole hardpans act as a physical barrier to root penetration, the tobacco obtained most of its water in the 15 to 25 cm. of the plow zone (De Roo, 1957). The use of soil moisture was estimated by gravimetric sampling of the plow layer of the Merrimac sandy loam of a field set to tobacco on June 14, 1957. Cores were taken from four locations in five replicates and the use of water estimated by difference: initial storage in the plow zone plus rainfall and irrigation minus final storage and leaching. Fortunately, leaching occurred only once.

During the first period, June 20 to July 8, much of the soil between the small plants was exposed to sun, and as expected, the loss of soil moisture was reduced by mulches of either white-pigmented or black polyethylene film which lay upon the soil and hindered the evaporation of moisture from the soil, Table 11.

During the second period, July 8 to August 22, the soil became dry, especially where it was bare. The moisture beneath the film was more readily available to the plants; the consequent increase in transpiration was greater than the saving in evaporation from the soil and the covered plots lost more water than the bare ones. If the difference in soil moisture between bare and mulched plots was partially removed by five irrigations, the plastic covering again caused a saving in soil moisture, Table 11. Thus, a mulch of film simply stops evaporation from the soil, and wherever this evaporation is large, the stoppage saves water which will

Table 11. Total millimeters input and loss of water from tobacco fields during two periods.

Irrigation	Covering	Input		Use	
		6/20 to 7/8	7/8 to 8/22	6/20 to 7/8	7/8 to 8/22
No	None	34	96	51	104
	White	34	96	43	114
	Black	34	96	43	114
Five	None	34	216	....	153
	White	34	189	....	135
	Black	34	198	....	132

meet later demands for transpiration and, thus, benefit the plant. The effect upon transpiration, evaporation from the leaves, is more subtle.

Transpiration requires energy. Wherever a reflective mulch is placed beneath a tall, isolated plant, the leaves will receive more energy from beneath while still receiving the same from above. If the leaves receive more energy above the reflective surface, then transpiration must be increased from each square centimeter of leaf. A geometrical analysis predicts that transpiration will increase one-eighth to one-fifth above aluminum foil that has been in the field for a month or above light tan paper; it predicts that transpiration will change less than one-tenth above hay, above black film, or above translucent film that has been in the field for a month. No increase would be expected if the surface were entirely shaded or if the leaves were lying on the surface (Waggoner and Reifsnyder, 1961).

The actual effect of mulches upon evaporation from an evaporator, such as a leaf, supported above a largely sunlit soil or mulch was estimated by means of atmometers supported 37 cm. above the soil. These black, wet, spherical bulbs were used instead of plants because their consumption of water had a coefficient of variation of only 2 per cent compared to 75 for the plants tested; these atmometers were models of long-stemmed plants without the plants' variability. The bulbs were supported above the centers of four 4.6 by 4.6 m. plots, and the evaporation was measured every day or two until each bulb had been once above bare soil, above paper, above hay, and above black plastic.

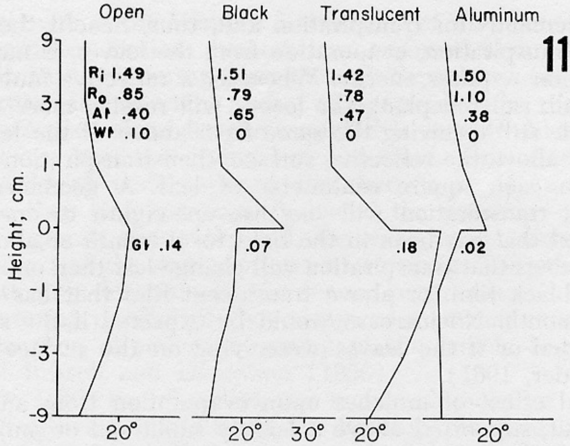
The relative evaporation on five clear to partly cloudy July days was: bare, 100; paper, 112; hay, 103; black, 102. The evaporation was consistently higher above the reflective paper than above the dark hay, black plastic, and bare soil. Evidently a leaf above a sunlit paper or foil mulch will transpire more than a leaf above bare soil or hay, black film, or dusty translucent film (Waggoner and Reifsnyder, 1961).

Clearly, the water economy of a plot and the plants upon it can be changed by a mulch. The film stops evaporation from the soil, and if the film reflects sunlight against the leaves above, it can increase transpiration.

A Summary, Temperatures Above and Below the Mulches

The temperatures in the air above and below the mulches and in the soil below are summaries of the effects of the mulches and will be reviewed before we conclude our climatology of the mulches and turn to their effects upon plants.

The four temperature profiles of Figure 11 demonstrate the operation and results of three mulches on a clear day. The black film absorbs much and reflects little insolation, thus gaining much despite a high temperature and thermal radiation; it can conduct little of this downward, because of the underlying air, and the soil beneath remains cool; consequently, the film itself becomes hot and conducts large amounts of energy to the atmosphere. The translucent film transmits much insolation to the soil beneath; the upward loss of energy from the soil is difficult because the layer of air beneath the film is still and the film absorbs and radiates long waves; thus energy is conducted into the soil,



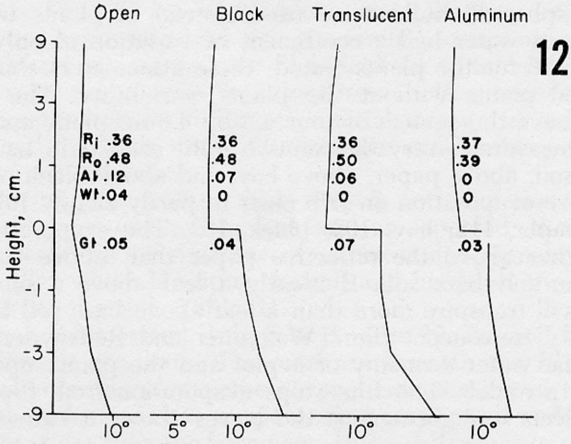


Fig. 11. Temperature profiles and energy flux density at 1210 hours on October 12, 1958.

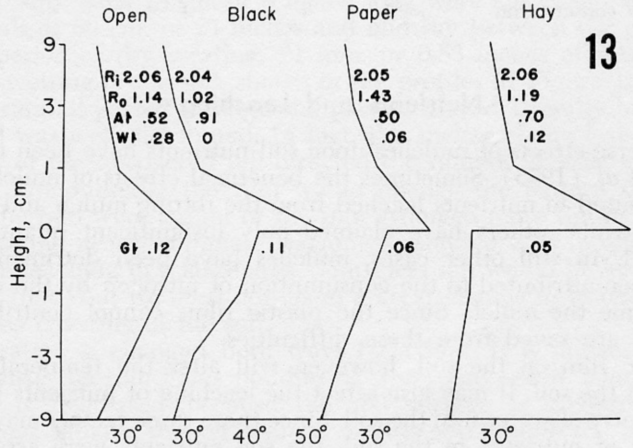
Fig. 12. Temperature profiles and energy flux density at 0020 hours on October 12, 1958.

and it is warmed. The aluminum film reflects much, absorbs some and transmits no insolation; like the black film, it can conduct little energy downward, but unlike the black film, the aluminum remains cool; thus the soil beneath remains very cool.

The nighttime profiles in Figure 12 reveal the behavior of the three mulches on a clear night. Radiation cools all films beneath the cold night sky, but the energy is replaced only slowly through the still air between soil and film, leaving the protected soil warm. The aluminum loses somewhat less energy because its emissivity is low, and the translucent film more because the soil beneath is warm; but all covered soil remains warmer than the exposed soil.

Hay and paper mulches can be compared to black film and bare soil, Figure 13. The observations were taken on a clear day. The paper reflects some insolation and transmits a bit; little energy is conducted through the air beneath the paper; thus the soil remains cool. The hay absorbs fully as much insolation as the bare soil; little energy is conducted through the insulating litter; the surface of the hay becomes hot and conducts large amounts of energy to the atmosphere; thus the soil remains cool while the surface becomes torrid.

The nighttime profiles in Figure 14 show the behavior of mulches on a clear night. The paper, unlike aluminum, emits as much radiation as bare soil, and hence, the soil beneath cools somewhat despite the tempering of the air between paper and soil. The surface of the hay, overlying a multitude of insulating air layers, becomes cool itself, increasing the danger of frost in plant shoots while permitting the soil to remain warm. Clearly, a variety of soil climates can be produced with the five mulches.



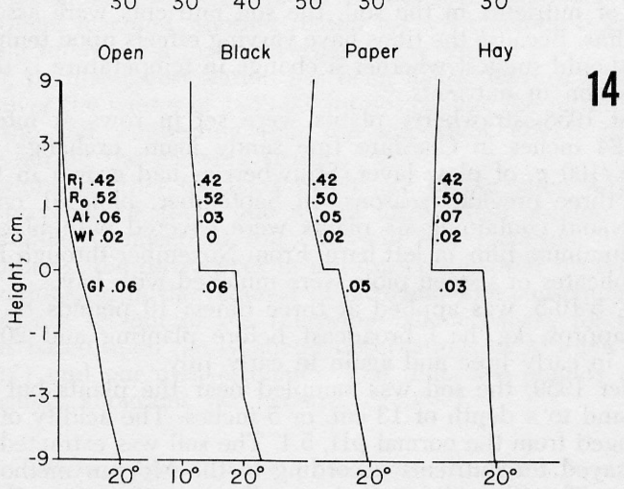


Fig. 13. Temperature profiles and energy flux density at 1144 hours on June 11, 1959.

Fig. 14. Temperature profiles and energy flux density at 2335 hours on June 11, 1959.

The effects of mulches on temperature may be summarized in another way. When a change in climate would be expected to favor a crop, this change may be among those that can be effected by one of the five coverings, as here tabulated:

	Black film	Trans-lucent film	Aluminum foil	Kraft paper	Hay
Ground heat storage	−	+	− −	−	− −
Midday soil surface temperature	0	+ +	−	−	− −
Nocturnal soil surface temperature	+	+	+	0	+
Mean soil temperature, −3 cm.	0	+	0	−	−
Diurnal range, −3 cm.	−	+	− − −	−	− −
Soil moisture conservation	+ +	+ +	+ +	+	+

Nutrients and Leaching

The diverse effects of mulches upon soil nutrients have been reviewed by Jacks *et al.* (1955). Sometimes the beneficial effects of mulches have been attributed to nutrients leached from the rotting mulch and into the soil; meanwhile, others have claimed only insignificant quantities are contributed. In still other cases, mulches have been detrimental, and this has been attributed to the consumption of nitrogen by the microbes that consume the mulch. Since the plastic films cannot contribute nutrients, we are saved from these difficulties.

A plastic film on the soil, however, will alter the temperature and moisture of the soil. It may also affect the leaching of nutrients by localizing the entry of water into the soil. Since these three factors may change the supply of nutrients in the soil, the soil nutrients were assayed beneath the films. Because the films have varying effects upon temperature, the assays should suggest whether a change in temperature is the cause of any variation in nutrients.

In August 1958, strawberry plants were set in rows at intervals of 60 cm. or 24 inches in Cheshire fine sandy loam, exchange capacity = 11.6 m.e./100 g. of plow layer. Strawberries had grown in the field during the three previous seasons. In September, plots 91 cm. or 36 inches wide and containing six plants were covered with black, translucent, or aluminum film, or left bare. From November through February the four replicates of sixteen plots were mulched with hay.

Fertilizer, 5-10-5, was applied at three times: 10 pounds of nitrogen per acre (approx. kg./ha.) broadcast before planting and 20 pounds sidedressed in early June and again in early July.

In October 1959, the soil was sampled near the plants but beneath the plastic and to a depth of 13 cm. or 5 inches. The acidity of the soil was unchanged from the normal pH, 5.4. The soil was extracted and the leachate assayed for nutrients according to the Morgan method (Lunt *et al.*, 1950). The films did not change the quantity of available ammonia, phosphorus, potassium, calcium, magnesium, aluminum, or manganese. The indications of nitrate concentration were, however, consistently higher beneath the films than beneath a bare surface. Therefore, the nitrate in the soil was determined quantitatively by the phenol disulfonic acid method (Bear and Salter, 1916).

The mean nitrate nitrogen concentrations in parts per million of soil were: bare, 4; black, 33; translucent, 18; aluminum, 19. The standard error of a difference between these means of four replicates is 7. Thus the film-covered plots held significantly more nitrates than the bare and the black-covered plots held more than the other covered plots.

Differences in leaching are a possible cause of these differences in nitrate concentration. Hence, we must investigate the pattern of rainfall infiltration before discussing the nitrate concentrations. Plastic was spread between rows of tobacco that was growing on Merrimac sandy loam. The joint between two sheets of plastic was secured along the plant row by wires and soil, leaving little opening for water penetration. Two slits, each 15 cm. or 6 inches long were cut in the form of a T at intervals of 60 cm. or 24 inches and midway between the plant rows. After a period of dry weather, 21 mm. or 0.83 inches of rain fell. The depth of wetting in the soil, shown in the profiles of Figure 15, revealed that the rainfall passed through the plastic, moved laterally beneath the film, and was well distributed. In fact, the shelter of the leaves and the elevation of the uncovered hill directed the rainfall at least as much as the film. Undoubtedly the film would change the pattern of leaching more if the rain were lighter or the film arranged more tightly about the stems, causing nearly complete leaching of soluble salts in one spot and negligible leaching in a large area. Thus, less salt would be leached from an entire field, but we must not claim a great change in leaching following a loose covering of the soil.

Evaporation is changed both ways by a film. It is increased after a rain because the film holds puddles of water exposed to sun and wind. Later it is decreased because the soil surface is sheltered. In the Connecticut climate, the net result is moister soil (Table 15) and, hence, more frequent leaching, another reason for not claiming a great change in leaching following a loose covering of the soil.

A final, pertinent observation has been made. Covering the soil with mulches over the winter of 1959-60 did not change the nitrate concentration in the soil, suggesting that the important effects of the films occurred during the growing season.

The failure of other nutrients to change in the same way as nitrate and the presence of about one ton of nitrogen in organic form in an acre of similar Connecticut soil (Morgan and Jacobson, 1942) led to this hypothesis: the differences in nitrate were caused by differences in mineralization and in the removal of nitrogen. The consequences of this hypothesis are set out in the following balance sheet for nitrate; the balance is based upon the lysimeter observations of Morgan and Jacobson (1942) and our own estimates. The units are pounds per acre or approximately kilograms per hectare.

	Nitrate =	Initial +	Added +	Mineralized −	Crop use −	Weed use −	Leached
Bare soil	8	8	50	40	20	20	50
Black	66	8	50	58	20	0	30
Translucent	36	8	50	58	20	20	40
Aluminum	38	8	50	30	20	0	30

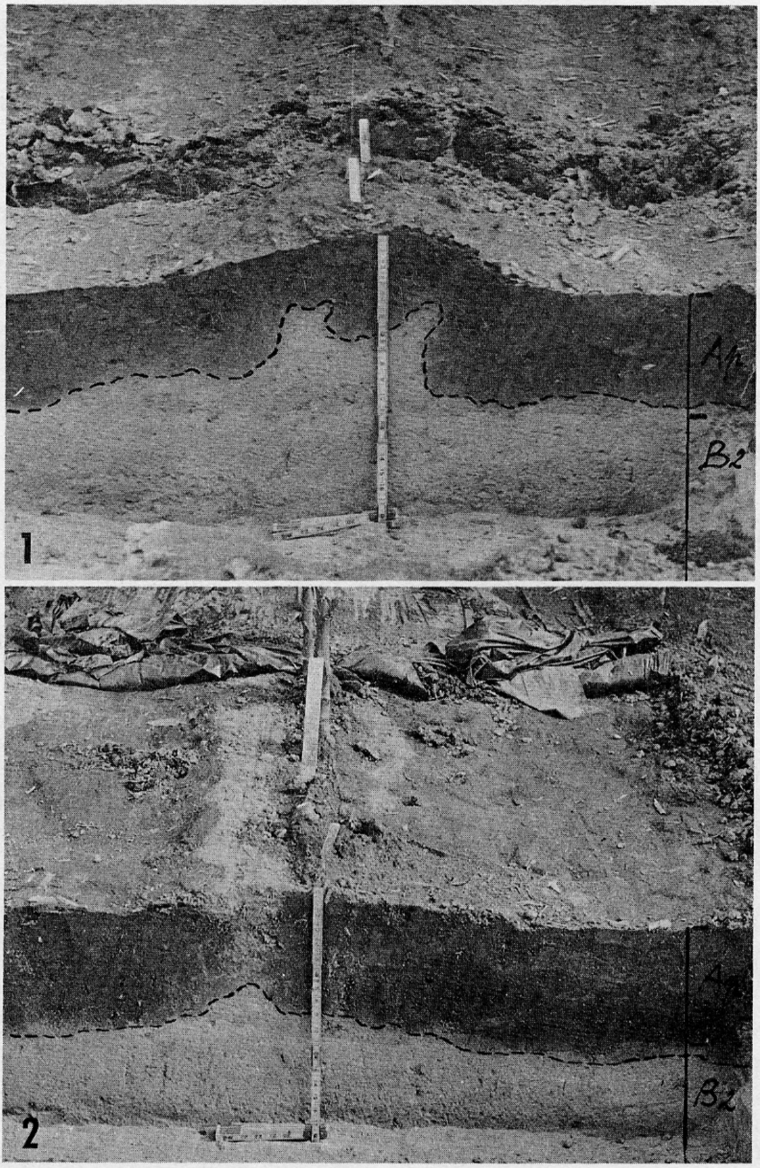


Fig. 15. The penetration of rain into (1) cultivated soil and into (2) soil covered by film.

The first column contains the observations of October 1959. The second column contains the quantity observed beneath the bare soil in October 1959, a quantity that could be expected in all plots in the preceding autumn when the plastics were installed. The third column contains the amount of nitrogen added in fertilizer. The release of nitrogen, from organic matter in the bare soil, column four, was set between the 48 pounds observed in an unfertilized lysimeter soil planted to tobacco and the 12 pounds observed in one receiving 200 pounds of nitrate of soda per acre. This mineralization of nitrogen was set higher for the warm and moist soil beneath the black and translucent and lower for the cool soil beneath the aluminum film. The fifth and sixth columns contain estimates of crop and weed use which are each equal to the removal by the sparse crop of tobacco which grew upon a lysimeter that received no nitrogenous fertilizer; being sparse, the tobacco resembled the widely-spaced strawberries or the scattered weeds. The removal of nitrogen through leaching of the bare plot, last column, was set at about half the initial, added and mineralized nitrogen in accordance with lysimeter observations following the application of nitrate of soda. We estimated that the black and aluminum films reduced leaching of nitrogen by 20 and that the translucent film, which decomposed during the growing season, reduced leaching by only 10.

These gains and losses could have led to the quantities of nitrate observed in the soil in October 1959. Although they have the disadvantage of being estimates, they have the advantage of being an explicit exposition of the way changes in temperature, moisture and leaching beneath the films could change the nitrate to roots, an exposition that reflects the available observations. Any changes in nutrients, together with the changes in soil climate, will be reflected in the effects of the films upon the early growth of a perennial plant, strawberry.

Early Flowers and Fruit, Runners and Root Diseases of Strawberry

Plastic films provide an economical means of changing soil temperature and moisture. Whether plants will find these changes good or bad remained for us to test in the field. These changes should have a pronounced effect upon perennial plants early in the season when temperatures are apt to be too cool for rapid growth. The effect of the changes may not be directly upon the plants: they don't grow alone but together with their pests. Therefore, we have examined the effect of the climates of mulches upon the perennial strawberry, whose early fruits are esteemed and whose roots are plagued by pests.

Three experiments have been performed on the Cheshire fine sandy loam of the Lockwood Farm. In August of 1957, sixteen plots of Stelemaster strawberries were set in soil that had grown strawberries for several years. The plots were divided into four replicates of plots, each containing five plants at intervals of two feet. Plots were left bare or covered with black or translucent polyethylene or with aluminum film. During the following year all blossoms were removed, runners were counted and roots were weighed and examined for discoloration. In September of 1958, we set a similar experiment in the same field with six Stelemaster plants in sixteen 12-foot plots. During the following growing season, this second set of plots revealed the effect of mulches upon blossoming and fruit production and produced further data on runner production and root diseases. In September of 1959, we set twenty-five plots in a Latin square on soil that had not grown strawberries within memory. Each plot was 6 by 6 feet and contained six Stelemaster plants. The soil was left bare or was covered with hay, or with black, translucent, or green film. Unlike the preceding plots, these were not mulched with hay over winter. This last set of plots showed the capability of green film.

Blossoms and fruit

The appearance of blossoms and the yield of ripe fruit were observed in two diverse crops: in 1959 a small yield was collected from plants on old land and following a severe winter, while in 1960 a much larger yield was collected from plants on new land and following a milder winter.

The warmth of soil beneath translucent film hastened blossoming, Table 12. This was observed in both years despite the diversity of the crops. The green film, which provided a warmth intermediate between translucent film and bare soil, also hastened blossoming. The effects of other coverings, even the reflective aluminum, were small. Thus, we had seen how warming the soil with negligible warming of the air could accelerate one process of a plant. We had still to see whether it would be followed by the desired early fruit.

The plants growing in the warm soil beneath translucent film produced a spurt of fruit at the first picking. Then the increments of ripe fruit declined rapidly. In the short season of 1959, the initial spurt of the plants mulched with translucent conferred great advantage upon them, and their yield for the season was fully twice the yield from the plants in bare soil. In 1960 the season was longer, and the sustained increments of fruit from the check plants nearly overtook the accumulated yield of the translucent-mulched plants. Evidently the fruits were set in a shorter time on the mulched plants and they grew almost simultaneously, draining the plant's resources and preventing the usual largeness of the first fruits.

Table 12. Blossoms and yields of strawberries accumulated by several dates on plots of 6 plants.

1959	Bare	Black	Translucent	Aluminum
Blossoms, May 5	4	6	27	7
Ripe fruit, May 27, weight/number	0 g./0 berries	0/0	34/7	3/1
Ripe fruit, June 3	8/2	12/3	76/16	14/4
Ripe fruit, June 10	52/12	62/14	117/25	39/12

1960	Bare	Black	Translucent	Green A	Hay
Blossoms, May 5	1	2	23	8	0
Blossoms, May 9	9	14	41	26	3
Ripe fruit, June 2	18 g./2 berries	55/4	132/16	82/7	0/0
Ripe fruit, June 7	136/16	230/26	295/42	271/33	112/10
Ripe fruit, June 13	247/40	351/53	364/58	383/57	272/37
Ripe fruit, June 29	331/60	413/69	381/65	443/71	395/63

The plants mulched with green film were in soil of intermediate warmth and produced a spurt of early fruit intermediate between check and translucent mulch. Here the setting of fruit was apparently more extended, the size of the first fruit was not reduced, yields were sustained and the yield for the season as well as for the first week was significantly increased. A further inference is also tenable: in the mild spring of 1960 the temperatures beneath the translucent became too warm for the strawberries' best growth, while those beneath the green remained temperate.

In 1960 the black film, which increased the daily minimum temperature but scarcely affected the maximum, increased the increment in yield at all save the last picking. Thus, although the initial picking was not greatly increased, the yield for the 1960 season was increased significantly by the black film. In 1959 when the plants grew upon land that had grown strawberries for several years, the outcome was quite different: the black film had no consistent effect.

The hay, unlike the black film, decreased the maximum daily temperature while increasing the minimum. Thus, one is not surprised to see that the initial harvest was decreased, the final harvest increased, and the harvest for the season not materially changed. The aluminum film produced a similar temperature course in the soil, but its effect upon the plants was insignificant in 1959.

Already we can see the predominant effect of soil temperature upon the springtime growth of the perennial strawberry. The flowering and fruiting were speeded wherever the soil climate was warmed and slowed wherever the climate was cooled. Evidently the diurnal range was unimportant because the translucent film, which increased the range, increased the early yield of fruit; and the black film, which decreased the range, did not decrease the early yield of fruit. Further, the conservation of soil moisture was unimportant because the translucent film and the hay both conserved water but had opposite effects upon earliness. Finally, the conservation of nitrate likely had no effect because on May 12, 1960 we added nitrate of soda at the rate of 35 kg. of nitrogen per hectare or pounds per acre.

Runners

The production of runners and, hence, new plants by the strawberry is another indication of the vigor of the plants as well as an important practical matter. In 1958 the fruits were removed from the plants as soon as they were set, permitting treatment differences to appear clearly. The number of runners produced in three separate periods in May and June was significantly greater where the soil was covered by the translucent film than in the other three cases, Table 13. The differences among

Table 13. Strawberry runners produced per plant during three periods, 1958.

	Mulch			
	None	Black	Translucent	Aluminum
To May 28	1.1	2.8	5.0	1.1
May 28 to June 5	2.4	3.0	4.6	2.4
June 5 to June 23	7.7	8.7	11.2	7.7

the other films and bare soil were insignificant. All runners present were removed on May 28 and June 5.

Later, the number of runner plants formed between June 5 and August 11 was counted. These were, of course, formed on runners grown during the same period, June 5 to August 11. Where the translucent film lay, the number formed per plant was consistently but not outstandingly greater than the number formed by other plants:

No film	Black	Translucent	Aluminum
55	75	84	67

Had the runners not been removed on May 28 and June 5, the advantage of the translucent film would undoubtedly have been greater. Although less than those mulched with translucent, the plants mulched with black and aluminum film produced significantly more runner plants than did those on bare soil. Thus the formation of runners during the spring may not be favored by the moisture beneath the opaque films, but the formation of runner plants during the dry summer is favored by opaque films that stop evaporation.

The young fruits were not removed from the plants in 1959. When the runners were counted on June 27, no differences existed among the four treatments despite the heavy crop of fruit produced by the plants grown upon soil covered with translucent film.

A final observation can be brought to bear upon this problem. The number of runners upon the plants was counted on May 25, 1960. Being early, the runners were not yet numerous, but neither were the fruits large. The scarce runners do not permit the demonstration of significant differences, but they take on interest from their consistency with the blossoming. The mean numbers of runners per plant were:

No mulch	Black film	Translucent film	Green A film	Hay
0.1	0.4	0.6	0.5	0.1

Evidently, runners and runner plants, like blossoms and fruits, are aided by the warm soil and increased diurnal temperature range beneath the translucent or the partly translucent green film. The roots, which are actually in the modified climate beneath the films, must be the site of the action that creates the increased activities already seen.

Roots

By the end of April 1958, the strawberry roots set the preceding autumn had existed in the modified soil climates for eight months. On April 25 one root system was excavated from each plot by means of a spade, the root washed in a bucket of water, and the root promptly weighed. The mean fresh weights in grams for the four replicates were:

No film	Black	Translucent	Aluminum
9	8	11	9

The warm soil beneath the translucent film had caused the early growth of significantly more roots than grew in the soil of the other plots.

Later, on June 24, a single root system from each treatment was excavated in a monolith (De Roo, 1957); by this time, with low temperatures no longer limiting growth, we found no evidence of more roots beneath the translucent film. In the following year, ten plants were excavated on October 22. No consistent differences in the quantity of roots were found among the treatments. Thus, we concluded that the increased production of fruit and runners that followed the warming translucent mulch was caused by the increased growth and activity of roots during the cool early spring and not by improved rooting throughout the growing season.

That the mulches were not an unmixed blessing was suggested by the appearance of the roots: in April 1958 those roots that grew beneath the three films had more brown lesions upon them than did those that grew beneath a bare surface. Therefore, we examined the pests upon the roots.

Diseases

Whenever a host and parasite are brought together, the occurrence of a plant disease is conditioned by the environment. If the soil environment is changed, as we have changed it with the mulches, the incidence of root disease will almost surely vary. We could hope that the change would favor the host, but the decision had to be sought in the field experiments. The superficial examination of the roots excavated in April 1958 indicated that the change would not be good.

First, we counted the nematodes in the soil. Soil samples showed no consistent difference in numbers of meadow nematodes among the treatments. Therefore, we turned to fungal parasites.

Rhizoctonia solani was the suspected culprit. It was known to be in the field, and it grows upon and kills strawberry roots. Therefore, in the autumn of 1959, we estimated the activity of *Rhizoctonia solani* Kühn in the sixteen plots. This was accomplished by taking two soil samples from each plot on October 25 and growing fifteen *Rhizoctonia*-susceptible lettuce seedlings in each sample. Some of the seedlings died. Because the dead plants showed both the signs and symptoms of *Rhizoctonia* infection, the mortality is an index of the activity of *Rhizoctonia* in the soil. When transformed into arc sine of the square root of the mortalities, according to usual statistical practice, these indices showed significantly more activity of the fungus in the soil from beneath the translucent, black, and aluminum film than in the bare soil, Table 14. They also showed significantly more activity beneath the black than beneath the other films.

Next we examined the actual incidence of the fungus upon strawberry roots in the field. Segments of fine strawberry roots 1 mm. or less in diameter were taken from the soil samples of October 25, 1959. The segments were washed free of soil and two lots from each plot were mounted in lactophenol on separate slides. Then the number of hyphal fragments of *Rhizoctonia* were counted on 2 cm. of root segments on each slide. The square roots of these numbers plus one-half were analyzed as indices of the infection of strawberry roots by the fungus. They showed significantly more infection beneath the three films than beneath the bare soil, they showed significantly more infection beneath

Table 14. *Rhizoctonia* and strawberries.

	Mulch			
	None	Black	Translucent	Aluminum
Mortality of lettuce, an index of *Rhizoctonia* in the soil	58%	89	70	79
Hyphal fragments per 2 cm. of root, an index of infection	4.0	16.3	5.3	9.2
Mortality of strawberries in the field	17%	50	21	33

black than beneath the other films, and they showed significantly more infection beneath aluminum than beneath translucent film, Table 14.

The mortality of the strawberries themselves is a final and critical estimate of the disease in the plots. Since only twenty-four plants were contained in the four replicates, a useful statistical test is impossible. However, the actual mortality of the host in the plots is a helpful measure of the validity of our assays of infestation and infection. These mortalities are given in Table 14 and show the same order as the other assays: the environment beneath the black film is least healthy, that beneath the bare surface is most healthy, and the other film-covered environments are intermediate. We can now summarize our conclusions concerning the growth of strawberries in mulched soil.

Summary

When one is concerned with the growth of a perennial crop, especially its growth during the cool spring months, the mulches that transmit radiation and warm the soil are the ones that benefit the plants. This was shown in the early blossoming and the early and abundant fruit and runners produced by strawberries mulched with natural or green translucent film. The parts of the plant that actually grew in the warmed environment, the roots, grew more than those beneath other films or bare soil. Since the shoots are essentially at the same temperature above all of the surfaces in our small plots, this increased root activity must be the cause of the increased growth of the shoots. Later, during warmer weather, we saw no effect of the films upon the roots.

The benefits of the plastics were not realized without a cost to the plant. The roots beneath the films were attacked more by the pathogenic *Rhizoctonia solani* than were those growing in bare soil. The attack was particularly severe beneath the black and aluminum films, which kept the soil moist without warming it materially. This is understandable because the depredations of this fungus are favored by cool as well as by moist soil.

Warmth is critical to these springtime events, but when we turn to summertime phenomena, all of the films were beneficial because of their ability to conserve moisture through their obstruction of evaporation. Thus the production of runner plants during the summer was increased by all films. When we examine the growth of tobacco during the warm summer months, we shall see more of this benefit from moisture.

Roots and Leaf Quality of Tobacco

The plastic films, when placed upon the soil, can keep the soil moist as well as change its temperature. This more copious supply of water surely affects plant growth.

Tobacco is an excellent indicator of the results of increased soil moisture. First, in Connecticut it grows upon shallow roots in a sandy soil. Second, it grows rapidly and is sensitive to drought during the months of July and August, months of high evaporation and frequent drought. Finally, the quality or color of the cured leaves is not only an important attribute, it is also a characteristic that is sensitive to drought. For example, a part of the effect upon quality of the picturesque "shade" or cheesecloth tents is undoubtedly due to their reduction of evaporation and creation of a more favorable soil moisture regime (Waggoner *et al.*, 1959). Thus, a so-called shade type of tobacco was grown without shade as an indicator of the effect of the conservation of soil moisture.

An experiment was performed on the Merrimac sandy loam at the Tobacco Laboratory in Windsor. On June 6, 1957 thirty plots of the B 106 variety of tobacco were set in the open. Since this variety of tobacco is ordinarily grown in a tent, the experimental plots were set adjacent to similar plants growing in a shade tent. The plots consisted of 3 rows 90 cm. or 3 feet apart; each row consisted of sixteen plants set at intervals of 36 cm. or 14 inches. The plots were divided into five randomized blocks, each containing a set of three plots that were irrigated and a set of three that received only the scant rainfall that fell in 1957, Table 11. On June 11 to 14 the soil of one plot in each set was covered with black polyethylene film, 38 μ thick, and the soil of one plot was covered with white-pigmented film of the same thickness. The third plot remained bare and was cultivated approximately according to standard practice.

Subsequently we learned that on a sunny day the white film decreased by 8° C. the midday temperature of the soil at a depth of 1 cm., while the black film behaved in the manner described in earlier sections.

The reality of the moister soil beneath the mulches can be seen in the frequency distributions of soil moisture concentrations, Table 15. On twelve days between July 1 and August 22, the soil moisture was determined gravimetrically from four cores taken from 0 to 15 cm. or

Table 15. The frequency of soil moisture concentrations on 12 days between July 1 and August 22, 1957. Samples at a depth of 0 to 15 cm. or 6 inches.

Irrigation	Covering	Soil moisture, percentage of dry weight >13	13–10	9–7	<7
None	None	0	33	33	33
	White	17	42	25	17
	Black	17	42	25	17
Five	None	0	33	67	0
	White	17	50	33	0
	Black	17	42	42	0
Three	Tent	17	25	50	8

6 inch depth and adjacent to the center row of each plot. The means for each date and for each treatment were calculated and their frequency distributions set down in the table. Clearly high moisture concentrations and low soil moisture stresses were more frequent in the plastic-covered soil than in the bare soil, a change that was also created by irrigation or a shade tent. The five irrigations of bare and film-covered plots created ampler moisture than the three irrigations beneath the tent. The stresses that correspond to the tabulated moisture concentrations can be surmised from the characteristics of this soil: soil moisture is at field capacity at 16 and at the wilting percentage at 4 per cent of dry weight in the Merrimac sandy loam of these plots. This sandy soil releases about two-thirds of its available moisture at tensions less than 2 bars or atmospheres (Hill, 1959). Having seen the moister soil environment created by the films, we shall now see how this affected root distribution.

Root distribution

The distribution of the roots beneath plastic can cause concern if one simply lifts the film, looks beneath, and sees a mat of superficial roots. In fact, the presence of these shallow roots caused the condemnation of a paper mulch for tobacco (Anderson, 1932, and personal communication). Therefore, we examined the effect of plastic mulch upon the distribution of the entire root system.

On September 23, a monolith of soil and roots was impaled upon a pin board and excavated from each treatment (De Roo, 1957). The shallow roots common to mulched plants were in evidence beneath the film, Figure 16.

Of course, the absence of deep roots, not the presence of shallow ones, is the crux of this matter. As the photographs, Figure 16, and relative weights, Table 16, of the root systems show, the film did not discourage deep roots, even in the drier, non-irrigated soil. Neither the color of the film nor irrigation affected deep rooting. Evidently a plastic mulch has no deleterious effect upon the deeper distribution of roots and the consequent anchorage and exploitation of reserves of nutrients and water. The shallow roots beneath the plastic were an addition and not a subtraction from the usual root system. Therefore, one expects that the moister soil beneath the film will lead to larger plants.

Stem growth

At intervals the height of stems and the area of leaves in the center row were measured. The height of the tobacco stems on June 28 was increased by covering the soil with film, black or white, Table 17.

The mechanism through which the increase was worked can be seen in the course of growth from June 28 to August 2: irrigation, like mulch, increased the relative growth from 16 to a range of 18 to 21 fold, while the film had scant effect upon relative growth in irrigated plots. Further, the change in soil temperature caused by two colors of film had no effect. Thus, plastic mulch increased the growth of tobacco by increasing the amount and availability of soil moisture, and on August 2 the mulched soil had produced taller plants than the bare soil.

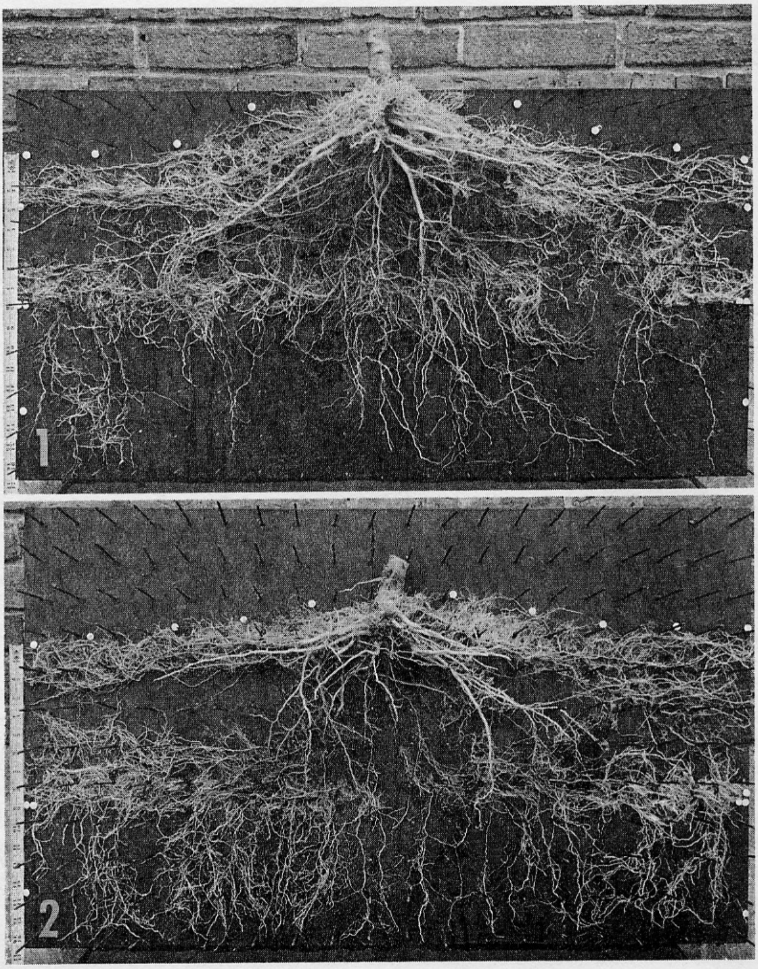


Fig. 16. The roots produced by a shade type of tobacco in (1) bare soil and in (2) soil covered by black film.

Table 16. Relative weights of tobacco roots. Relative weight is the weight of oven-dry roots in 10 cm. or 4 inches of profile divided by the dry weight of the entire system of roots below 15 cm. or 6 inches.

		Horizon and approximate depth		
Irrigation	Covering	Ap_2 15 to 30 cm.	B_2 30 to 43 cm.	B_3 43 to 53 cm.
None	None	62	13	4
	White	49	13	8
	Black	53	13	4
Five	None	52	5	0
	White	58	7	5
	Black	52	12	3

Table 17. Mean heights of forty tobacco stems.

Irrigation	Covering	Height in cm. June 28	July 12	August 2	Height on Aug. 2/ height on June 28
None	None	6.9	27	113	16
	White	8.4	31	144	18
	Black	8.1	33	148	18
Three	None	5.8	23	120	21
	White	7.6	30	161	21
	Black	7.6	30	150	20
Three	Tent	8.6	29	146	17

If our goal for the plastic mulches is the imitation of the shade tent, an ill omen can be seen in Table 17. On June 28 the shade-grown plants were the tallest. However, their relative growth from then until August was less than seen in either irrigated or mulched plots. This is not surprising because the shade of the tent should be particularly limiting to photosynthesis when the plants are large and shade one another. As we turn to the growth and quality of the leaf, we cannot expect that the mulches will mimic the tent.

Leaf area and weight

The plants growing in soil covered by film produced larger leaves than those growing in bare soil. Unlike stem elongation, the film increased leaf area even in irrigated plants. Evidently leaf expansion benefited from the slightly increased frequency of high soil moisture beneath mulch, even in irrigated plots, Table 15.

Once again the effect of tent and mulch are not equivalent. The tent produced the largest leaves in the lowest positions, exceeding the leaves from mulched plants by one-quarter, but the higher and later leaves were about the same in shaded and in sunlit, mulched plots.

The quantity of dry matter in a unit area of leaf is a measure of leaf thickness, one of the principal characteristics which determines the quality of the leaf. Unfortunately, the only markedly thinner leaves were those produced in the shade of the tent. Nevertheless, we shall see that the treatments did change another indicator of leaf quality.

Color of cured leaves

The quality of a plant—its color, physical properties, smell, or chemical composition—can be as interesting or valuable as its quantity. A shade type of tobacco is an excellent indicator of any changes in quality caused by the mulches because some colors are prized for cigar wrappers and other colors render it nearly worthless; these colors are profoundly influenced by the environment, as we shall see.

Leaves were harvested, cured, and fermented before sorting into grades. The leaves were "primed" in the usual fashion by removing two to four of the lowest leaves at the times when they were judged "ripe." The leaf positions and primings are numbered from the bottom to top

Table 18. The frequency of colors in cured leaves of tobacco. About 100 leaves in each sample.

Leaf Position	Priming	Irrigation	Covering	Colors: Light Brown	Mottled	Green	Dark
8, 9 and 10	4	None	None	0	3	31	65
			White	0	34	9	57
			Black	0	30	45	25
		Five	None	4	11	53	31
			White	8	40	35	17
			Black	6	22	36	35
		Three	Tent	29	49	22	0
3, 4 and 5	2	None	None	5	33	39	24
			White	10	51	15	24
			Black	7	39	28	26
		Five	None	0	33	28	40
			White	3	25	25	47
			Black	3	17	25	54
		Three	Tent	18	36	38	7

of the stem. After the leaves were processed, commercial graders sorted the leaves into eleven classes according to the grade requirements of their warehouse. We grouped these eleven grades according to their color, the main characteristic on which the leaves were sorted, Table 18.

The availability of soil moisture clearly increased the frequency of light brown and mottled leaves: these colors were more numerous (Table 18) where mulches covered moist soil (Table 15) than where the soil was bare and more frequently dry. The color of the mulch and the change in soil temperature had little effect.

As before, the tent had an effect that was not wholly produced by increased availability of water. Although the soil beneath the tent was frequently drier than the soil beneath the film, Table 15, the tent produced the highest frequency of light brown and mottled leaves. The reduced light, transpiration and drought beneath the tent (Waggoner *et al.*, 1959) could not be wholly mimicked by the moist soil beneath the plastic film. Or, the tent has effects beyond the provision of moist soil. Nevertheless, so great was the change in leaf constitution caused by the film and a change in soil moisture alone, that varied color could still be detected after weeks of curing.

Summary

The diverse optical natures of plastic films create new surfaces and new distributions of energy at the earth's face, modifying the soil climate in predictable directions. The changes in soil temperature bring spring noticeably earlier or later to the perennial strawberry plant. Later, the conservation of soil moisture increases the growth of shallow roots, of leaf area, and of stem height of the annual tobacco; it even changes the composition of this plant.

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