The quantitative relationship between weed emergence and the physical properties of mulches

John R. Teasdale
Corresponding author. USDA-ARS Weed Science Lab, Bldg. 001, Room 323, Beltsville, MD 20705; teasdale@ba.ars.usda.gov

Charles L. Mohler
Department of Ecology and Evolutionary Biology. Corson Hall, Cornell University, Ithaca, NY 14853

Mulches on the soil surface are known to suppress weed emergence, but the quantitative relationships between emergence and mulch properties have not been clearly defined. A theoretical framework for describing the relationships among mulch mass, area index, height, cover, light extinction, and weed emergence is introduced. This theory is applied to data from experiments on emergence of four annual weed species through mulches of selected materials applied at six rates. Mulch materials, in order from lowest to highest surface-area-to-mass ratio, were bark chips, Zea mays stalks, Secale cereale, Trifolium incarnatum, Vicia villosa, Quercus leaves, and landscape fabric strips. The order of weed species’ sensitivity to mulches was Amaranthus retroflexus > Chenopodium album > Setaria faberi > Abutilon theophrasti, regardless of mulch material. The success of emergence through mulches was related to the capacity of seedlings to grow around obstructing mulch elements under limiting light conditions. Mulch area index was a pivotal property for quantitatively defining mulch properties and understanding weed emergence through mulches. A two-parameter model of emergence as a function of mulch area index and fraction of mulch volume that was solid reasonably predicted emergence across the range of mulches investigated.

Nomenclature: Abutilon theophrasti Medicus ABUTH, velvetleaf; Amaranthus retroflexus L. AMARE, redroot pigweed; Chenopodium album L. CHEAL, common lambsquarters; Setaria faberi Herrm. SETFA, giant foxtail; Quercus alba L., white oak; Quercus montana Willd., chestnut oak; Secale cereale L., rye; Trifolium incarnatum L., crimson clover; Vicia villosa Roth, hairy vetch; Zea mays L., corn.

Key words: Residue, litter, cover crop, light extinction, seedling, ABUTH, AMARE, CHEAL, SEFTA.

Weed management models that predict the biological and economic benefits of potential weed control interventions rely on accurate predictions of weed emergence (Lybecker et al. 1991; Swinton and King 1994). Several approaches have been taken to modeling weed emergence. Forcella (1998) has developed a model, WeedCast, that uses daily temperature and moisture data to predict the timing of cumulative emergence of several important weed species. Alm et al. (1993) proposed a model that separates germination and emergence processes; this approach requires seed depth as well as temperature and moisture data to predict weed emergence. Mohler (1993) developed a model that explains weed emergence based on the redistribution of seeds in the soil profile by tillage operations, the survival of seeds at different depths, and the emergence potential of seedlings from specified depths.

Residue on the surface of soils can influence the emergence of most plant species. Facelli and Pickett (1991a) reviewed the influence of surface litter on plant emergence and community structure in natural systems. Crop residues remaining on the soil surface in minimum-tillage agricultural operations can reduce weed emergence (Buhler et al. 1996; Vidal and Bauman 1996). Cover crops can produce high levels of residue biomass that suppress weed emergence and contribute to integrated weed management systems (Mohler and Teasdale 1993; Teasdale 1998; Williams et al. 1998). Therefore, residue is an important factor that should be incorporated into weed emergence models.

Although there are many reports on weed suppression by plant residue and mulches, not many have assessed the quantitative relationship between residue and weed emergence (Teasdale 1998). Earlier research demonstrated the relationship between mass of Secale cereale or Vicia villosa residue, soil microclimate (Teasdale and Mohler 1993), and weed emergence (Mohler and Teasdale 1993). There is a need to define more precisely the physical properties of a wide range of mulch types and determine their relation to weed emergence. The purpose of our research was to determine functional relationships between mulch physical properties and weed emergence. Materials with a range of area-to-mass ratios were chosen to provide mulches with widely differing physical properties. Abutilon theophrasti, Setaria faberi, Chenopodium album, and Amaranthus retroflexus were chosen as representative annual weed species that vary in seed size and are important in many areas of the world. This paper focuses on the relation between final emergence values and mulch physical properties; a subsequent paper will analyze the influence of mulches on soil temperature and emergence timing.

Materials and Methods

Experiments were conducted on a silt loam soil in 1996 and 1997 at Beltsville, MD. The field was plowed in the fall and disked and cultipacked in the spring just before establishment. One day was required to establish each rep-
lication. Three replications per year were established on May 2, May 15, and June 4 of 1996 and on May 7, May 14, and June 11 of 1997. Each replication contained seven mulches (Zea mays stalks, S. cereale, Trifolium incarnatum, V. villosa, Quercus leaves, bark chips, and landscape fabric strips) applied at six rates plus three to five unmulched control plots. Plots were 1 by 2 m divided into two 1- by 1-m sections, one for assessment of weed emergence and one for mulch measurements. In the middle 0.25-m² area of the weed emergence section, seeds of A. theophrasti, S. faberi, C. album, and A. retroflexus were planted in 50-cm-long rows at the rate of 150 seeds per species at a depth of 1 cm. This field had a low resident population of weeds; A. theophrasti and S. faberi were absent, and A. retroflexus and C. album emergence was less than 1 seedling m⁻². Following planting, residue was added to the soil surface according to a completely randomized design within each replication. Bird netting was secured over plots of lighter residue to prevent dispersion by wind.

Mulch Properties

T. incarnatum, V. villosa, and S. cereale residue were obtained from local fields, transported to the experiment site, and spread to dry along the edge of the field in a layer approximately 15 to 30 cm deep within 1 wk of establishing plots. Z. mays stalks that had overwintered from the previous season were obtained from a nearby field. Quercus leaves (primarily a mixture of Q. alba and Q. montana) were raked from the edge of a nearby forest. Bark mulch¹ was purchased from a local nursery. Landscape fabric² was cut into strips and mixed at a 2:1 ratio (wt:wt) with 15-cm green plastic twist-ties.

The six rates of application were determined by weighing the amount of mulch material that provided 40% coverage of the soil and preparing lots with masses equal to 1, 2, 4, 8, 16, and 24 times that amount. This procedure gave a wide range of mulch rates with the 4× rate being approximately equivalent to the natural residue levels produced by S. cereale, V. villosa, and T. incarnatum in Maryland. Lots for all replications of Quercus leaves, bark, and fabric were prepared before initial experimental setup. Lots of Z. mays, T. incarnatum, V. villosa, and S. cereale mulches were prepared on the same day that each replication was established. Three samples of all materials were collected at the time of lot preparation, weighed immediately to determine a fresh mass, and weighed after drying to determine a dry mass. All plot residue rates were converted to dry mass by multiplying the fresh mass of material added to plots by the dry-to-fresh-mass ratio determined from the samples.

The surface area (one side) of a sample of residue elements was determined photometrically³ and then weighed to estimate the area-to-mass ratio (A₂₄ m² g⁻¹) for each mulch. The area-to-mass ratio was multiplied by the dry mass of mulch on each plot (M [g m⁻²]) to determine the mulch area index (MAI [m² of mulch area per m² of ground area]) for each plot:

MAI = A₂₄ · M.  

[1]

The structure of a mulch can be conceptualized as layers of randomly distributed elements. The height (H) of a mulch can then be computed as H = (number of layers) · (height of each layer). The number of layers can be expressed as Number of layers = MAI / (area index of one layer). If all the elements in each layer were uniformly aligned, then the area index of each layer would approach 1 and the number of layers would approach the MAI. However, with randomly distributed elements, the area index of each layer will be less than 1 and the number of layers will exceed the MAI. The height of each layer can be described as: Height of each layer = hₜ · (element irregularity factor) where hₜ (mm) is the mean thickness of mulch elements. The element irregularity factor refers to any feature that could cause a greater separation between layers than the thickness of each element such as twisting or curling of Quercus leaves or branch roots on Z. mays stalks. The irregularity factor ranges in value from 1 for elements with no irregularity to values increasingly greater than 1 for elements with increasingly greater irregularity. The height (H [mm]) of a mulch with element thickness (hₜ) can then be expressed as H = MAI · hₜ · (irregularity factor) / (area index per layer).

If Aₕ is defined as (area index per layer) / (irregularity factor) · hₜ, then mulch area index can be related to height by an expression analogous to that relating mulch area index to mass:

MAI = Aₕ · H.  

[2]

When hₜ is multiplied by Aₕ, the solid volume fraction (Vₗ) can be defined as:

Vₗ = Aₕ · hₜ = MAI · (hₜ / H) = (area index per layer) / (irregularity factor).  

[3]

The solid volume fraction is a measure of the fraction of mulch volume occupied by the mulch elements. Mulch height was measured at four predetermined locations in each plot. Based on Equation 2, the coefficient Aₕ was determined for each mulch material from the linear regression of MAI on H. The mean thickness of mulch elements (hₜ) was determined from measurements on three samples of 10 randomly selected mulch elements. Based on Equation 3, Vₗ was calculated by multiplying the measured value of hₜ by the coefficient Aₕ.

The extinction of light through a leaf canopy can be described by T = exp(-k · LAI) where T is the fraction of light transmitted, LAI is the leaf area index, and k is the light extinction coefficient (Hatfield 1998). An analogous expression can be described for the fraction of light transmitted through a mulch as a function of the mulch area index:

T = exp(-k · MAI).  

[4]

Light transmittance through the mulch of each plot was measured by inserting a line quantum sensor¹ into a slot made in the soil surface under the mulch. A stake with dimensions similar to those of the sensor was installed in the soil surface just before plot setup and removed just before light measurements to leave a slot for the sensor. Simultaneous measurements were made with the line sensor and with a second unobstructed quantum sensor within an hour of solar noon approximately 2 wk after plot establishment. The fraction of light transmitted was computed from the ratio of these measurements adjusted for the measured difference in sensor readings when both sensors were unobstructed. A light extinction coefficient (k) was computed for each mulch by regression of the transmittance values.
Weed Emergence

Weeds emerging within 2.5 cm of the planted row were counted approximately weekly for 10 to 12 wk and removed with forceps without disturbing the mulch elements. Seedlings were counted only if cotyledons of the broadleaved species or the first leaf of S. faberi were displayed and if the seedling had emerged above the locally surrounding mulch elements. Emergence occurred primarily in a 1- to 3-wk period during the first month after setup of each replication. Only weeds emerging during this initial flush were used for analysis since this allowed weed emergence and mulch properties to be associated at a single point in time as described below.

To account for changes in mulch properties during the experiment, mulch mass from a 0.5-m\(^2\) area and mulch height were measured at 5 to 6 wk and again at 10 to 12 wk after setup of each replication. Residue was washed free of soil and dried before measuring mass. The change in mulch mass and height over the short time period of this experiment was satisfactorily described by a linear function. Furthermore, this rate of change was proportional to the initial mulch mass or height value (i.e., the relation between rate of change and the initial value was linear). Therefore, mulch mass was determined at time \(t\) by the equation \(M_t = M_i (1 - d \cdot t)\) where \(M_i\) is the initial mass and \(d\) is a rate coefficient determined for each mulch (Wagner-Riddle et al. 1996). An analogous equation was used to determine mulch height at time \(t\). From these data, the mulch mass and height at the time of 50\% weed emergence in the unmulched plots was determined. The mulch area index at 50\% emergence was determined by multiplying the area-to-mass ratio by the mass at time \(t\).

The number of weeds that emerged in each mulched plot was divided by the mean number that emerged in the unmulched plots in the same replication to give the fraction of weeds that emerged (E). Two exponential models were used to explore the functional relationship between the fraction emergence and mulch mass at the time of 50\% emergence of the unmulched control for each replication and year. One model was a simple exponential decay function:

\[
E = \exp(-b_M \cdot M) \tag{5}
\]

with a single parameter, \(b_M\). The other function,

\[
E = (1 + a_M \cdot M) \cdot \exp(-b_M \cdot M), \tag{6}
\]

was a more general function with two parameters, \(a_M\) and \(b_M\), that describes an initial increase in emergence at low mulch rates followed by an exponential decline. The need for Equation 6 was tested by determining whether \(a_M\) was significantly different than zero. Since \(a_M\) was not found to be different than zero for almost every species and mulch, Equation 5 was used in all subsequent analyses.

By combining Equations 1 and 5, an equation for emergence as a function of mulch area index was derived:

\[
E = \exp(-b_M \cdot MAI / A_m) = \exp(-b_A \cdot MAI) \tag{7}
\]

where \(b_A = b_M / A_m\). Likewise, an equation for emergence as a function of mulch height was derived from Equations 2 and 7:

\[
E = \exp(-b_h \cdot A_h \cdot H) = \exp(-b_H \cdot H) \tag{8}
\]

where \(b_H = b_A \cdot A_h = b_M \cdot A_h / A_m\).

The coefficients \(b_M, b_A, \) and \(b_H\) were determined for each replication and year. An analysis of variance was conducted on these coefficients to test for mulch, weed species, year, and replication effects. Data were pooled based on the outcome of these analyses.

Preliminary analysis of the relation between the emergence coefficient (\(b_A\)) and the solid volume fraction (\(V_s\)) across all mulches demonstrated a significant fit to the model \(b_A = b_v \cdot V_s^{*v}\), suggesting that including \(V_s\) in the emergence model might produce a more general model. By substituting this relation between \(b_A\) and \(V_s\) into Equation 7, the following two-parameter model was derived:

\[
E = \exp(-b_v \cdot MAI \cdot V_s^{*v}). \tag{9}
\]

Likewise, the emergence coefficient (\(b_A\)) was significantly related to the light extinction coefficient (\(k\)) according to the model \(b_A = b_k \cdot k^{\alpha}\) leading to a similar two-parameter model:

\[
E = \exp(-b_k \cdot MAI \cdot k^{\alpha}) \tag{10}
\]

These models were tested by fitting them to the full data set with all mulches. Variance accounted for by the two-parameter model was compared with one-parameter models Equations 5, 7, and 8 and to a seven-parameter model that was Equations 5, 7, and 8 but with a separate coefficient for each of the seven mulches.

**Results and Discussion**

Analysis of variance showed no significant effects or interactions involving year or replication (with one exception discussed below), but there were significant interactions between mulch and species. Weather was similar in the two years. Rainfall was sufficient to provide good emergence conditions in both years, averaging 29 and 19 mm wk\(^{-1}\) in 1996 and 1997, respectively, during the first 5 wk after setup. Soil temperature differed little between seasons. As a result, analyses were performed for each mulch by species data set pooled over years and replications. Mulch properties were similarly pooled except for mulch degradation that differed between years.

**Mulch Properties**

The physical dimensions and structure of the mulches studied in these experiments varied considerably (Table 1). The area-to-mass ratio (\(A_m\)) was low for bark chips and Z. mays stalks and high for Quercus leaves and fabric mulch. Our value of \(A_m\) for Z. mays was lower than that reported by Gregory (1982); however, our measurements were made primarily on stalk residue in the spring, whereas Gregory reported on residue including leaves and husks collected in fall. Our values for legume residue were similar to the range of values reported by Gregory (1982) for Glycine max (L) Merr. (soybean). Our value for S. cereale is similar to values reported by Gregory (1982) for Triticum aestivum L. (wheat) and Wagner-Riddle et al. (1996) for S. cereale early in the season.

Mulch area index was linearly related to height over most of the range of values for all mulches (data not shown).
There was a slight upward deviation from linearity for some mulches at very high mulch rates suggesting that these mulches became slightly more compressed at high rates. The $A_h$ values shown in Table 1 correspond to area index per unit height values over the linear portion of these graphs. Generally, those mulches with lower $A_m$ values also had lower $A_h$ values.

The solid volume fraction ($V_s$) is a measure of the mulch volume occupied by mulch material. If the mulch elements were perfectly packed, they would occupy all of the volume and $V_s$ would equal 1. Bark and *Z. mays* mulches were the most highly packed with 64 and 50% of the mulch volume occupied, respectively (Table 1). *V. villosa*, *S. cereale*, and *T. incarnatum* mulches were intermediate with 16 to 27% of volume occupied. *Quercus*-leaf and fabric mulches had the most empty volume with only 5 to 7% of the volume occupied. These data demonstrate that most mulches have a relatively high fraction of empty volume.

A light extinction coefficient ($k$) equal to 1 is the expected value for randomly distributed black elements when the only light transmitted is direct radiation reaching soil uncovered by mulch (Wagner-Riddle et al. 1996). Values less than 1 indicate that diffuse, reflected radiation also contributes to transmittance. The coefficients derived in our experiments ranged from approximately 0.8 to 0.9 for *S. cereale*, *Z. mays*, and bark to approximately 0.5 for the other mulches (Table 1). The solid volume fraction and extinction coefficients were correlated ($r = 0.83$) suggesting that more empty space within a mulch may contribute to more reflected light.

The mass of the bark, *Z. mays*, fabric, and *Quercus* mulches exhibited little or no change during the short period of these experiments (Table 1). *S. cereale*, *T. incarnatum*, and *V. villosa* decomposed faster in 1996 than 1997; the legume mulches lost approximately one-third of their mass during the initial month of 1996. Lower *T. incarnatum*, *V. villosa*, and *S. cereale* decomposition rates in 1997 may have been caused by lower total rainfall and more windy, drying conditions in that year.

**Weed Emergence**

Weed emergence declined exponentially with increasing mulch rates according to Equation 5 for almost every mulch and species. A stimulation of emergence at low mulch rates as described by Equation 6 has been reported under conditions when legume mulches have been used (Blum et al. 1997) or when soil moisture was more favorable for emergence under mulched than unmulched conditions during droughty periods (Buhler et al. 1996; Mohler and Teasdale 1993). Because moisture conditions were favorable for emergence in both years of these experiments, it would be expected that the exponential relationship in Equation 5 predominated over that described by Equation 6.

The exceptional response was that of *A. retroflexus* to the legume mulches *V. villosa* and *T. incarnatum* in 1996 (Figure 1). In this year, *A. retroflexus* emergence was stimulated at

![Figure 1. Amaranthus retroflexus emergence (E) as a function of mulch mass (M). Models were E = (1 + 0.00778-M)exp(-0.00277-M) for 1996 ($R^2 = 0.43$) and E = exp(-0.00255-M) for 1997 ($R^2 = 0.59$). The coefficients in the 1996 model were significantly different than 0 indicating that the stimulation of emergence at low mulch rates was significant. Data for *Trifolium incarnatum* and *Vicia villosa* mulches were pooled for presentation because responses to mulches separately were not significantly different according to 95% confidence intervals.](image-url)
Table 2. Influence of mulch mass on weed emergence as expressed by the coefficient \( b_M \) in the regression \( E = \exp(-b_M M) \) where \( E \) is fraction emergence and \( M \) is mulch mass (g m\(^{-2}\)). \( R^2 \) values ranged from 0.64 to 0.87 for \( A. \ theophrasti \), 0.64 to 0.80 for \( S. \ faberi \), 0.54 to 0.71 for \( C. \ album \), and 0.45 to 0.81 for \( A. \ retroflexus \). Coefficients within species followed by the same letter are not significantly different according to 95% confidence intervals.

<table>
<thead>
<tr>
<th>Mulch</th>
<th>Abutilon theophrasti</th>
<th>Setaria faberi</th>
<th>Chenopodium album</th>
<th>Amaranthus retroflexus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric</td>
<td>0.00199 a</td>
<td>0.0047 a</td>
<td>0.0087 a</td>
<td>0.0126 a</td>
</tr>
<tr>
<td>Quercus</td>
<td>0.00076 bc</td>
<td>0.0013 b</td>
<td>0.0026 b</td>
<td>0.0063 b</td>
</tr>
<tr>
<td>S. cereale</td>
<td>0.00078 bc</td>
<td>0.0016 b</td>
<td>0.0020 b</td>
<td>0.0041 bc</td>
</tr>
<tr>
<td>T. incarnatum</td>
<td>0.00095 bc</td>
<td>0.0012 b</td>
<td>0.0015 b</td>
<td>0.0030c c</td>
</tr>
<tr>
<td>V. villosa</td>
<td>0.00105 ab</td>
<td>0.0012 b</td>
<td>0.0014 b</td>
<td>0.0023c c</td>
</tr>
<tr>
<td>Z. mays</td>
<td>0.00060 c</td>
<td>0.0010 b</td>
<td>0.0014 b</td>
<td>0.0023 d</td>
</tr>
<tr>
<td>Bark</td>
<td>0.00009 d</td>
<td>0.0001 c</td>
<td>0.0003 c</td>
<td>0.0006 d</td>
</tr>
</tbody>
</table>

*a Only 1997 data is included because 1996 data did not fit this model (see Figure 1).

Mulch masses up to approximately 200 g m\(^{-2}\) before declining exponentially at higher mulch rates. Blum et al. (1997) also observed a stimulation of \( A. \ retroflexus \) emergence by \( T. \ incarnatum \) residues in one year of their experiments; this stimulation was associated with an increase in soil nitrate. Gallagher and Cardina (1998) showed that nitrate could increase the dark germination of \( A. \ retroflexus \), particularly at intermediate temperatures. More rapid degradation of legume mulches in 1996 than 1997 (Table 1) may account for the difference in \( A. \ retroflexus \) emergence patterns between years in our experiments. Because Equation 5 adequately described the response of all weed species to all mulches with the exception of \( A. \ retroflexus \) response to legume mulches in 1996, only results fit with Equation 5 will be discussed for the remainder of the paper.

Higher values of the coefficient \( b_M \) in Equation 5 indicate more suppression of weed emergence by mulch. The order of sensitivity of the weed species tested was \( A. \ retroflexus > C. \ album > S. \ faberi > A. \ theophrasti \) for all mulches (Table 2). This order of sensitivity is similar to the inverse order of seed size (100-seed mass = 30, 49, 167, and 978 mg for \( A. \ retroflexus \), \( C. \ album \), \( S. \ faberi \), and \( A. \ theophrasti \), respectively). Mohler and Teasdale (1993) also found \( A. \ theophrasti \) to be less sensitive to \( S. \ cereale \) and \( V. \ villosa \) residue than smaller-seeded species. Data presented in Buhler et al. (1996) showed a similar order of species response to \( Z. \ mays \) residue when soil moisture conditions favored emergence.

Because the coefficients \( b_M \), \( b_A \), and \( b_H \) are proportional for any given mulch (Equations 7 and 8), the pattern of emergence response among weed species within mulch is the same for the variables mass, mulch area index, and height (Tables 2 to 4). However, because \( A_m \) and \( A_h \) are different for each mulch, the relative response of a species to different mulches is not the same for each variable (Tables 2 to 4).

Fabric mulch, with the highest area-to-mass ratio, was either the most or among the most suppressive mulches when compared on a mass or height basis, but was similar to many of the other mulches when compared on an area basis. Quercus leaf mulch, also having a high area-to-mass ratio, was intermediate when compared with other mulches on a mass or height basis but was among the least suppressive on an area basis. Bark mulch, with the lowest area-to-mass ratio, was the least suppressive on a mass basis but was among the most suppressive on an area basis.

Weed emergence response to the agronomic mulches \( Z. \ mays \), \( S. \ cereale \), \( T. \ incarnatum \), and \( V. \ villosa \) was similar with few exceptions when compared on a mass or height basis (Tables 2 and 4). Mohler and Teasdale (1993) also found \( S. \ cereale \) and \( V. \ villosa \) residue to be similarly suppressive on a mass basis. The emergence responses presented

Table 3. Influence of mulch area index on weed emergence as expressed by the coefficient \( b_A \) in the regression \( E = \exp(-b_A A) \) where \( E \) is fraction emergence and \( A \) is mulch area index (m\(^2\) m\(^{-2}\)). \( R^2 \) values ranged from 0.57 to 0.84 for \( A. \ theophrasti \), 0.66 to 0.82 for \( S. \ faberi \), 0.55 to 0.72 for \( C. \ album \), and 0.44 to 0.79 for \( A. \ retroflexus \). Coefficients within species followed by the same letter are not significantly different according to 95% confidence intervals.

<table>
<thead>
<tr>
<th>Mulch</th>
<th>Abutilon theophrasti</th>
<th>Setaria faberi</th>
<th>Chenopodium album</th>
<th>Amaranthus retroflexus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z. mays</td>
<td>0.31 a</td>
<td>0.55 a</td>
<td>0.73 a</td>
<td>1.22 ab</td>
</tr>
<tr>
<td>Bark</td>
<td>0.26 ab</td>
<td>0.38 ab</td>
<td>0.76 a</td>
<td>1.76 a</td>
</tr>
<tr>
<td>S. cereale</td>
<td>0.18 bc</td>
<td>0.39 ab</td>
<td>0.51 ab</td>
<td>1.00 bc</td>
</tr>
<tr>
<td>T. incarnatum</td>
<td>0.19 bc</td>
<td>0.24 bcd</td>
<td>0.28 bc</td>
<td>0.57 bc cd</td>
</tr>
<tr>
<td>V. villosa</td>
<td>0.16 bc</td>
<td>0.20 cd</td>
<td>0.23 c</td>
<td>0.45 d</td>
</tr>
<tr>
<td>Fabric</td>
<td>0.13 cd</td>
<td>0.30 bc</td>
<td>0.56 ab</td>
<td>0.80 bcd</td>
</tr>
<tr>
<td>Quercus</td>
<td>0.08 d</td>
<td>0.13 d</td>
<td>0.25 c</td>
<td>0.60 cd</td>
</tr>
</tbody>
</table>

*a Only 1997 data is included because 1996 data did not fit this model (see Figure 1).

Table 4. Influence of mulch height on weed emergence as expressed by the coefficient \( b_H \) in the regression \( E = \exp(-b_H H) \) where \( E \) is fraction emergence and \( H \) is mulch height (mm). \( R^2 \) values ranged from 0.46 to 0.76 for \( A. \ theophrasti \), 0.44 to 0.79 for \( S. \ faberi \), 0.46 to 0.85 for \( C. \ album \), and 0.42 to 0.69 for \( A. \ retroflexus \). Coefficients within species followed by the same letter are not significantly different according to 95% confidence intervals.

<table>
<thead>
<tr>
<th>Mulch</th>
<th>Abutilon theophrasti</th>
<th>Setaria faberi</th>
<th>Chenopodium album</th>
<th>Amaranthus retroflexus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric</td>
<td>0.021 a</td>
<td>0.048 a</td>
<td>0.070 a</td>
<td>0.137 a</td>
</tr>
<tr>
<td>Bark</td>
<td>0.013 ab</td>
<td>0.019 b</td>
<td>0.037 ab</td>
<td>0.077 a</td>
</tr>
<tr>
<td>Quercus</td>
<td>0.013 ab</td>
<td>0.019 b</td>
<td>0.037 ab</td>
<td>0.093 a</td>
</tr>
<tr>
<td>T. incarnatum</td>
<td>0.019 ab</td>
<td>0.024 b</td>
<td>0.028 bc</td>
<td>0.042 b</td>
</tr>
<tr>
<td>V. villosa</td>
<td>0.016 ab</td>
<td>0.019 b</td>
<td>0.023 bc</td>
<td>0.029 b</td>
</tr>
<tr>
<td>Z. mays</td>
<td>0.011 b</td>
<td>0.017 b</td>
<td>0.020 c</td>
<td>0.036 b</td>
</tr>
<tr>
<td>S. cereale</td>
<td>0.009 b</td>
<td>0.016 b</td>
<td>0.019 c</td>
<td>0.040 b</td>
</tr>
</tbody>
</table>

*a Only 1997 data is included because 1996 data did not fit this model (see Figure 1).
Table 5. Evaluation of selected models fit to the full data set pooled across all mulches.

<table>
<thead>
<tr>
<th>Number of model parameters</th>
<th>Variables</th>
<th>Model $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Abutilon theophrasti</td>
<td>Setaria faberi</td>
</tr>
<tr>
<td>1$^a$</td>
<td>M</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>MAI</td>
<td>0.62</td>
</tr>
<tr>
<td>2$^b$</td>
<td>MAI, $V_s$</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>MAI, $k$</td>
<td>0.68</td>
</tr>
<tr>
<td>7$^c$</td>
<td>MAI</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>0.58</td>
</tr>
</tbody>
</table>

$^a$ Parameter b in the model $E = \exp(-b \cdot X)$ where $E$ is fraction emergence and $X$ is M, H, or MAI.

$^b$ Parameters b and c in the model $E = \exp(-b \cdot MAI \cdot X^c)$ where $E$ is fraction emergence and $X$ is $V_s$ or k. Estimated values of $b$ were 0.37, 0.52, 0.71, and 1.54 when $X = V_s$ and 0.30, 0.52, 0.81, and 1.57 when $X = k$ for A. theophrasti, S. faberi, C. album, and A. retroflexus, respectively. Estimated values of c were 0.47, 0.38, 0.34, and 0.33 when $X = V_s$ and 1.28, 1.38, 1.49, and 1.34 when $X = k$ for A. theophrasti, S. faberi, C. album, and A. retroflexus, respectively.

$^c$ Parameters b, to b, in the model $E = \exp(-b \cdot X)$ where E is fraction emergence, X is M, H, or MAI, and $b_k$ represents a separate parameter for each of the seven mulches. Parameter values are listed in Tables 2 to 4.

Here are similar to those described by Buhler et al. (1996) for the same weed species in response to Z. mays residue and by Vidali and Bauman (1996) for S. faberi in response to T. aestivum residue under favorable moisture conditions. When compared on a mulch area index basis (Table 3), Z. mays was more suppressive than both legumes, whereas S. cereale was intermediate between Z. mays and the legumes.

The range of values for weed suppression coefficients across mulches within a species is approximately 20- to 40-fold for mass and 2- to 4-fold for mulch area index and height (Tables 2 to 4). Thus, none of these coefficients will adequately describe emergence through all mulches. When one-parameter models with data from all mulches pooled were tested for predictive capability, the variable MAI was superior to mass or height in describing emergence (Table 5). This establishes the importance of MAI to understanding weed emergence through mulches and suggests that this property is critical to determining weed emergence through mulches. However, the best one-parameter models were clearly inferior to the best seven-parameter models that included a separate coefficient for each of the seven mulches (Table 5). This suggests that mulch properties other than MAI also contributed to weed suppression.

The two-parameter models that included both MAI and $V_s$ or k (Equations 9 and 10) improved the fit compared with the one-parameter models and approached the precision of the best seven-parameter models, particularly for the larger-seeded species (Table 5). Therefore, $V_s$ or k were important variables for describing the residual variation in the one-parameter models. The variables $V_s$ and k are highly correlated and both relate to the fraction of occupied mulch volume. Therefore, this analysis suggests that weed emergence through mulches is influenced primarily by MAI, a measure of the area of layers in a mulch, and by $V_s$, a measure of the available space within those layers. These properties appear to provide a basis for modeling weed emergence through all mulches.

**Emergence, Mulch Cover, and Light Extinction: Properties of the Coefficient $b_A$**

The coefficient $b_A$ that defines the relation between emergence and mulch area index has interesting descriptive properties. Gregory (1982) has shown that for randomly distributed mulch elements, the fraction of the soil covered by mulch ($C$) can be related to the mulch mass (M) by

$$C = 1 - \exp(-A_m \cdot M)$$  \[11\]

where $A_m$ is the element area-to-mass ratio described in Equation 1. By combining Equations 1, 7, and 11, an equation for the relation between fraction emergence, fraction of soil area covered by mulch, and fraction of uncovered soil (U) can be derived:

$$E = (1 - C)^{b_A} = U^{b_A}$$  \[12\]

Thus, emergence is related to the fraction of uncovered soil by the same coefficient, $b_A$, as that describing the relation between emergence and mulch area index. As formulated in Equation 12, the coefficient $b_A$ can provide biologically meaningful information. When $b_A = 1$, then the fraction of emergence is equivalent to the fraction of uncovered soil suggesting that weeds can only emerge from soil not covered by mulch (Figure 2). When $b_A < 1$, then the fraction emergence is greater than the fraction of uncovered soil suggesting that some seedlings can emerge beneath and grow around mulch elements. When $b_A > 1$, then the fraction emergence is less than the fraction of uncovered soil suggesting that factors other than physical impedance may be limiting emergence.

The assumption of random distribution of mulch elements in the derivation of Equation 11 has important implications for weed suppression by mulches. It means that mulches do not completely cover the soil even at levels that
might be expected to provide complete soil coverage. For example, material with a mulch area index of 1, 2, or 3 covers only 63, 86, or 95% of soil area, respectively, if randomly distributed but could cover all of the soil if uniformly distributed. Random distribution of mulch elements creates a heterogeneity within the mulch, thereby providing sites for weed emergence in seemingly high levels of mulch. This heterogeneity has been documented empirically by Facelli and Pickett (1991b) and Teasdale and Mohler (1993) for light penetration of various mulch materials. Because emergence is a function of the fraction of uncovered soil (Equation 12), we hypothesize that management practices that leave residue uniformly distributed should provide better weed suppression than practices that leave residue randomly distributed.

Emergence also can be related to light transmittance by combining Equations 4 and 7:

$$E = T^{k(b_A/k)}.$$  
[13]

If $b_A = k$, then the fraction of seedlings that emerge and light transmittance are reduced similarly by mulch (Figure 3). If $b_A < k$, then emergence exceeds transmittance indicating that seedlings can grow through mulch elements in diminished light. If $b_A > k$, then transmittance exceeds emergence indicating that factors other than light may be limiting emergence. The $b_A / k$ ratios for the mulches in these experiments are presented in Table 6.

By examining the $b_A$ coefficients (Table 3) and the $b_A / k$ ratios (Table 6) in our experiments, some generalizations about the response of emergence to mulches can be made. *A. theophrasti*, *S. faberi*, and *C. album*, with one exception, had both $b_A$ and $b_A / k$ coefficients $< 1$. This indicates that these species, after emerging from the soil, were able to grow around mulch elements that covered them and to grow in the absence of light. The inverse correlations of the $b_A$ and $b_A / k$ coefficients with the seed size of these weed species supports the theory that seed reserves probably determined the capacity of seedlings to grow through mulches in the absence of light.

*A. retroflexus* in the legume mulches had $b_A$ coefficients $< 1$ but $b_A / k$ coefficients approximately equal to 1 indicating that *A. retroflexus* had the capacity to grow around these thin mulch elements but could only grow in proportion to the light available. *A. retroflexus* in fabric and *Quercus* leaf mulches had $b_A$ coefficients $< 1$ but $b_A / k$ coefficients $> 1$. This situation can be explained by the capacity of *A. retroflexus* seedlings to grow around the edges of these relatively broad mulch elements for short distances when there is sufficient light but not for long distances even when light is available. *A. retroflexus* in *S. cereale*, *Z. mays*, and bark mulches had $b_A$ and $b_A / k$ coefficients $> 1$ indicating that factors other than mulch coverage and light extinction may have been limiting emergence through these mulches. *S. cereale*, *Z. mays*, and bark mulches had the lowest area-to-height ratios (Table 1) and, therefore, the light profile within these mulches would be expanded over a longer distance than in the other mulches. This suggests that *A. retroflexus* seedlings may not have been capable of growing longer distances to reach improved light conditions.

Table 6. The ratio of the coefficient $b_A$ (Table 3) to the light extinction coefficient $k$ (Table 1). This ratio defines the importance of light in controlling seedling emergence.

<table>
<thead>
<tr>
<th>Mulch</th>
<th><em>Abutilon theophrasti</em></th>
<th><em>Setaria faberi</em></th>
<th><em>Chenopodium album</em></th>
<th><em>Amaranthus retroflexus</em></th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Z. mays</em></td>
<td>0.36</td>
<td>0.64</td>
<td>0.85</td>
<td>1.42</td>
</tr>
<tr>
<td>Bark</td>
<td>0.27</td>
<td>0.40</td>
<td>0.81</td>
<td>1.87</td>
</tr>
<tr>
<td><em>S. cereale</em></td>
<td>0.22</td>
<td>0.48</td>
<td>0.63</td>
<td>1.23</td>
</tr>
<tr>
<td><em>T. incarnatum</em></td>
<td>0.35</td>
<td>0.44</td>
<td>0.53</td>
<td>1.05</td>
</tr>
<tr>
<td><em>V. villosa</em></td>
<td>0.32</td>
<td>0.40</td>
<td>0.46</td>
<td>0.90</td>
</tr>
<tr>
<td>Fabric</td>
<td>0.24</td>
<td>0.58</td>
<td>1.08</td>
<td>1.56</td>
</tr>
<tr>
<td><em>Quercus</em></td>
<td>0.17</td>
<td>0.28</td>
<td>0.56</td>
<td>1.34</td>
</tr>
</tbody>
</table>

We have focused on physical impedance and light availability to emerging seedlings as the dominant factors determining emergence while recognizing that other factors such as microclimate effects on seed germination and allelopathy also can influence emergence (Teasdale 1998). The seed lots used in these experiments had a low rate of dormant seed with 62, 86, 95, and 81% germination rates of *A. theophrasti*, *S. faberi*, *C. album*, and *A. retroflexus*, respectively, under optimum growth chamber conditions. Therefore, mulch effects on microclimate factors affecting dormancy probably had minimal effect on these seed lots. Allelopathic influences were probably minimal because mulches that have been associated with allelopathy such as *S. cereale*, *T. incarnatum*, and *V. villosa* (Teasdale et al. 1998; White et al. 1989) were fit equally with the same general equations (9 and 10) as relatively inert or highly weathered mulches such as bark, *Z. mays*, *Quercus* leaves, and synthetic fabric. Observation of residuals after fitting Equations 9 and 10 to pooled data indicated no pattern suggesting lack of fit by any mulch. Bosy and Reader (1995) also found that physical impedance by grass residue was the dominating effect in reducing seedling emergence compared with either microclimate effects on germination or allelopathy. Therefore, our results are most consistent with physical impedance and light depri-
vation as the principle mechanisms controlling emergence rates through these mulches.

An artificial seedbank was created for this experiment that was uniform but not necessarily similar to natural seed-banks. Seeds were mostly nondormant and were placed at an optimum 1-cm depth for emergence. Therefore, the models and coefficients presented in this paper represent the response to mulches of a weed seedbank that has optimum germination and emergence potential. Model adaptation may be needed to account for the influence of mulches on factors influencing dormancy status of weed seeds. Also, models may need adaptation to account for responses to mulches when weeds emerge from less optimum depths (deeper or shallower). For example, preliminary information suggests that Equation 6 may be more appropriate for seeds emerging from the soil surface (Mohler, unpublished results). Future research needs to investigate the interactions between mulches, seed dormancy, and seed depth to clarify the best modeling approach for describing emergence through mulches of weeds from natural seedbanks.

Source of Materials

1 Bark mulch, Pine Bark Nuggets, Kamlar Corp., 444 Kamlar Dr., Rocky Mount, NC 27804
2 Landscape fabric, Yard-Tech Brown Landscape Fabric, Agway, 213 S. Fulton St., Ithaca, NY 14850
3 Leaf Area Meter, Model LI-3100, LI-COR, Inc., 4421 Superior St., Lincoln, NE 68504
4 Quantum sensor, Model LI-191, LI-COR, Inc., 4421 Superior St., Lincoln, NE 68504

Acknowledgments

This project was funded in part by USDA NRICGP grant #95-37315-2018. The authors thank Fred Magruder, Joyce Lombardi, Matt Skidmore, Sara Moussavi, Paul Gerber, Michele Evancho, and Amy Ellis for their careful technical assistance on this project.

Literature Cited


Received April 20, 1999, and approved February 29, 2000.