Modeling Straw Mulch in Taos Agriculture

NM Supercomputing Challenge

Team: THS-31

Taos High School

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Executive Summary:

The goal of this project was to find the optimal amount of straw mulch to put down to minimize water related costs. To solve this optimum we modeled the evapotranspiration based on weather data collected in NM. Each year we here about the water resources such as the Ogallala Aquifer being drained. Furthermore, many farmers in the US are struggling financially. By finding a way to decrease water consumption, we can potentially save farmers thousands of dollars, while protecting water resources.

We built the model in MATLAB following a guide to computing evapotranspiration (ET). Our model seemed to work at first, however after working with the data we found that there were some errors. After going through the code again we found that there was a ratio that could not exceed 1.0, however the guide we had been using had omitted this detail. We found the ratio information on the official website of the FAO-56 method for the Penman-Monteith equation.

We found the error because our code was calculating negative ET. Furthermore, we found that the optimum was a negative value that indicated to us that there was probably some kind of error.

Introduction and Background Research:

Mulching reduces soil loss primarily by decreasing raindrop impact and runoff velocity. Mulching is also considered an effective method of manipulating crop growing environment to increase yield and improve the quality of the product through weed growth, the reduction of soil temperature, the conservation of soil moisture, reduction of soil erosion, and the improvement of soil structure [4]. This works whether the mulch applications are surface applied or surface incorporated, and depends on multiple other factors including the erosivity of the rainfall, the type of soil, the soil condition, the length and angle of the desired slope, and the type of mulch application used. As for choosing a mulch application most effective for soil erosion control, the most realistic selections are naturally occurring sources, and depend greatly upon cheap availability and land use. Another important factor in the determination of a particular mulch application is ease of management, particularly when the applied mulch is for annual cropping. Rate of application is considered to be the most important parameter of mulching, and previous research has shown that there is a correspondence between increased mulching rates and and decreased soil erosion up to an optimum mulching rate. The effectiveness of of erosion control varies depending on the slope. The more gentle the slope, the more effective the erosion control will be up to an optimum slope. As the slope of the cultivated increases, mulching requirement for effective erosion control increases.

Although the majority of published research in the field, (global effectiveness of using crop residues as mulch in soil erosion control), involved heavier mulch applications, research has shown that mulch applications of only 0.56 t/ha or lower could be effective on slopes as steep as 15% during drastic rainfall [2]. This is considerably beneficial considering most published research involved mulch applications of about five tons per hectare (t/ha).

Mulching improves biotic activity, adding nutrients to the soil, and therefore increasing soil fertility through decomposition [4]. The type of mulch application used determines the impact on physical and chemical properties of soil, as well as crop yield. The quality of different mulching applications is determined by the nutrient value, texture, rate of decomposition, availability, cost, growth rate and vegetative matter turn over. The residue quality of the mulch applications determines the nutritional effects that they have on the plants. Higher quality materials improve the nutrition of the plant by releasing excess nutrients, lower quality residues have a comparatively weak nutritional effect on the plants. The chemical composition of plants differ, therefore changing the rate decomposition and suitability as a viable mulch application. To test this, experiments were conducted on an Oxic Tropuldalf (an environment containing sandy loam soil), to study the effects of Chromolaena and Tithonia mulches on soil chemical properties, the nutrient composition of leaves, and growth and tuber yield of white yam [4]. As for the site where the experiment occurred, the surface and subsoil layers of the site were sandy loam in texture, with an increase in clay content as you got to the subsoil layers of the site [4]. Before adding the Chromolaena and Tithonia into the environment in 2006, there was a lack of organic matter, which was later attributed to the high bulk density of the soil. The content of organic matter and nutrients was higher at the surface levels of the Oxic Tropuldalf, and decreased regularly the deeper into the subsoil layers that was tested [4]. In the studies conducted, both Chromolaena and Tithonia both reduced soil bulk density and temperature. Both mulches also increased the content of Nitrogen, Phosphorus, Potassium, Calcium, and Magnesium in the soil as well as the leaves [4]. When compared with the control, the mulches also increased the growth and yield of yam. The findings showed that Chromolaena and Tithonia mulches increased the soil moisture content, and reduced the bulk density of the soil as well as the temperature. Both the higher moisture content and the lower temperature could be attributed to the reduction of evaporation losses [4]. The reduction of the soil bulk density observed in both the Chromolaena and Tithonia mulch applications compared with the unmulched control plots could be ascribed to the lower concentration of organic materials in the subsoil layers, as well as less aggregation, less root penetration, and compaction caused by the weight of overlying layers [4]. Organic matter reduces soil bulk density, improves soil structure, improves aeration, and enhances water infiltration and retention [4]. Using mulch applications increased activities of soil fauna in the decomposition of organic matter, leading to the enhancement of soil porosity and reduction of the soil bulk density. The mulch also stabilized the soil structure against raindrop impact, preventing any soil erosion, compaction or crusting.

Although there are many advantages for the agricultural sector by using plastic mulch, the widespread utilization of plastic mulch has begun to detriment the environment more than benefit it. The development of completely biodegradable plastic mulch applications was started by Chinese plastic companies to establish more sustainable and "greener" cultivation [5]. Some of the advantages to using plastic mulch applications are the conservation of water during crop production, as well as the suppression of weeds. Statistics showed that twenty million hectares of land in China used polyethylene film for cultivation, and the annual consumption of mulch film is increasing at an average annual rate of 10%. Economically speaking, mulch film is extremely beneficial and does yield more crop production than that of regular mulch applications, but there is also substantial ecological damage from using mulch film [5]. The accumulation of plastic mulch on arable land causes both ecological and environmental pollution, as well as the obstruction of crops' water and nutrient intake. This obstruction leads to as much as a 20% decrease in a crop's yield. There are two ways to alleviate pollution problems caused by mulch film, integration of biodegradable alternatives, and recycling [5]. Fully biodegradable plastic materials remain stable during use due to their special molecular structure, also allowing for complete decomposition after its service life. Full biodegradable plastic mulches are an ideal substitution for mulch films, and alleviate the impact that film residuals had on the environment.

There are many advantages to using completely biodegradable plastic mulch applications, starting with economic benefits. There are no labor costs for the reclamation of the film as it degrades after it completing its job. There is absolutely no risk of secondary pollution as it completely metabolizes in water, and finally the use of biodegradable mulch applications allows for complete control over its covering time, in turn allowing the product to be tailored specifically to the region in which it is used [5].

Project Description:

Model Parameters:

day	91-214 J	Day of the year in Julians
T_{max}	Degrees Celsius	Maximum temperature of each given day
T_{min}	Degrees Celsius	Minimum temperature of each given day
RHmax	%	Maximum relative humidity
RHmin	%	Minimum relative humidity
p	inHG	Pressure, later converted to kPa
wind	mph	Average wind speed in miles per hour, later converted to m/s

Parameters Explanation:

The weather parameters were based weather data collected at the Taos airport since 1993. Our final year of data was 2017. Data was broken up into years. Each year consisted of data starting on the first of April of the given year, and ending on the thirty first of October. The data was retrieved from the website of Weather Underground [1].

The rest of the parameters are based on available data gathered from various websites. All of the values were based on either Taos New Mexico, or in the event that the data was unavailable, we used values for New Mexico.

Method and Equations:

For our research we used the Penman-Monteith equation for Evapotranspiration, solved with the FAO-56 Method. The equation solves for Reference Evapotranspiration (ET_0). The equation listed below is based on the variables in Appendix 1.

$$ET_0 = \frac{.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + .34u_2)}$$

The first part of our code reads excel spreadsheets and puts them into arrays for each weather data so that we can calculate day by day. Each call is for a single year.

```
day = xlsread('Weather Data 1993-2018.xlsx',year(j),'A2:A215');
RHmax= xlsread('Weather Data 1993-2018.xlsx',year(j),'D2:D215');
RHmin= xlsread('Weather Data 1993-2018.xlsx',year(j),'E2:E215');
p = xlsread('Weather Data 1993-2018.xlsx',year(j),'F2:F215');
Wind = xlsread('Weather Data 1993-2018.xlsx',year(j),'G2:G215');
Tmin = xlsread('Weather Data 1993-2018.xlsx',year(j),'C2:C215');
Tmax = xlsread('Weather Data 1993-2018.xlsx',year(j),'B2:B215');
```

The University of Florida (UF) department of Agricultural and Biological Engineering produced a report in 2010, edited in 2015, that described the step by step methodology for calculating ET_0. In the project we followed their guide. The first step is to calculate the mean daily temperature. In their guide they explain that if only average daily temperatures are available it can be calculated, however it might result in some underestimation of ET due to the saturation vapor pressure being non-linear [3]. As a result, they advise the use of maximum and minimum daily temperature.

```
Tmean = (Tmax + Tmin)/2;
```

Once the mean daily temperature is calculated the guide instructs us to calculate the mean daily solar radiation. Because the weather station we used did not monitor solar radiation, we used monthly averages for New Mexico. This code works by making an array with the daily value based on the month, where Ri is the daily average based on the month.

```
Ri = [9.6, 10.6, 10.9, 9.9, 9.2, 8.3, 7.0];
Rmda = [];
for i = 1:length(day)
    if 1 <= day(i) && day(i) <= 30
        Rnettemp = 3.6 * Ri(1);
        Rmda = [Rmda, Rnettemp];
    end
    if 31 <= day(i) && day(i) <= 61
        Rnettemp = 3.6 * Ri(2);
        Rmda = [Rmda, Rnettemp];
    end
    if 62 <= day(i) && day(i) <= 91
        Rnettemp = 3.6 * Ri(3);
        Rmda = [Rmda, Rnettemp];
    end
    if 92 <= day(i) && day(i) <= 122
        Rnettemp = 3.6 * Ri(4);
        Rmda = [Rmda, Rnettemp];
    end
    if 123 <= day(i) && day(i) <= 153
        Rnettemp = 3.6 * Ri(5);
        Rmda = [Rmda, Rnettemp];
    end
    if 154 <= day(i) && day(i) <= 183
        Rnettemp = 3.6 * Ri(6);
        Rmda = [Rmda, Rnettemp];
    end
    if 184 <= day(i) && day(i) <= 214
        Rnettemp = 3.6 * Ri(7);
        Rmda = [Rmda, Rnettemp];
    end
    if 215 <= day(i) && day(i) <= 365
        Rnettemp = 3.6 *Ri(7);
        Rmda = [Rmda, Rnettemp];
    end
end
Rmd = Rmda';
```

Next calculate average daily wind speed at 2m above the surface. Our weather data includes the average wind speed, however as it was measured at about 9m, we have to run a conversion. We got the conversion formula from the UF document.

```
windms = Wind*0.44704;
windconverter = (4.87/(log(67.8*8.3536-5.42)));
Wind2 = windms*windconverter;
```

Using the mean daily temperature data, we previously calculated we calculate the slope of the vapor saturation pressure curve. Again, we use the UF paper for the formula.

```
slope_vapor_pressure_curve = (4098*(.6108*exp((17.27*Tmean)./(Tmean+237.3)))))./((Tmean + 237.3).^2);
```

As we have mean daily pressure we do not use their standardized pressure calculation, we do however convert the inches Hg that our weather data is in to kPa that their guide uses. Once pressure has been calculated, use it to calculate the Psychrometric constant.

```
Pressure = p*3.38639;
Psychrometric_constant = .000665*Pressure;
```

Next, we solve the Delta Term, a calculation for the radiation related ET. TO solve we use the slope of the saturation vapor pressure curve, the psychrometric constant, and the wind speed at two meters.

```
Delta_term = slope_vapor_pressure_curve./(slope_vapor_pressure_curve + Psychrometric_constant.*(1+.34*Wind2));
```

After that, we calculate the Psi Term (PT), and the Temperature Term (TT), both are for the Wind related ET calculation. These are based on the psychrometric constant, slope of the saturation vapor pressure curve, wind speed at 2m, and mean daily temperature.

```
PT = Psychrometric_constant./(slope_vapor_pressure_curve + Psychrometric_constant.*(1+0.34*Wind2));
TT = (900./(Tmean + 273)).*Wind2;
```

Next, we calculated the mean saturation vapor pressure. We do this by calculating the mean with max temperature and with min temperature, then averaging the two values.

```
Emin = .6108*exp((17.27*Tmin)./(Tmin+237.3));
Emax = .6108*exp((17.27*Tmax)./(Tmax+237.3));
Es = (Emax+Emin)/2;
```

Next we calculate the actual vapor pressure (AVP) using RHmax, RHmin, Emax, and Emin.

```
AVP = Emin.*((RHmax/100)+Emax.*(RHmin/100))/2;
```

Next we calculated the inverse relative distance between the Earth and the Sun, the solar declination, the latitude in radians, and the sunset hour angle. To do this we use the latitude in degrees and the day of the year.

```
Dr = 1+.033*cos(((2*pi)/365)*day);
declination = 0.409*sin(((2*pi)/365)*day-1.39);
lat_dec_deg = 36.75;
lat_rad = pi/180*lat_dec_deg;
sunset_hr_angle = acos(-tan(lat_rad)*tan(declination));
```

Next we calculated for extraterrestrial, clear sky, and albedo value radiation based on the solar constant, the inverse relative distance (calculated above), the sunset hour angle,the latitude in radians, elevation, and solar declination. To calculate the albedo value we calculated for it based on the value of straw, the value of soil, and the percent surface covered by each material.

```
Rextra = 1440/pi*.082*Dr.*(sunset_hr_angle*sin(lat_rad).*sin(declination))+(cos(lat_rad)*cos(declination).*sin(sunset_hr_angle));
```

```
Rclearsky = (.75+(2*(10^(-5)))*2163)*Rextra;
Bare = xlsread('imagedata.xlsx','Sheet1','B2:B14');
Straw = xlsread('imagedata.xlsx','Sheet1','C2:C14');
if Bare(m) == 0
    Albedo = .28;
end
if Straw(m)==0
    Albedo = .15;
end
if Bare(m)~= 0 && Straw(m)~= 0
    Albedo = .15*Bare(m) + .28*Straw(m);
end
```

Next, we calculated net shortwave radiation, net longwave radiation, and net radiation. We calculated these with the albedo value, mean daily radiation, Stefan Boltzmann constant, maximum daily temperature in kelvins, minimum daily temperature in kelvins, actual vapor pressure, and clear sky radiation.

```
Rnetshort = (1-Albedo)*Rmd;
if Rclearsky > Rmd
    Rnetlong = (4.903*10^-9)*(((Tmax+273.16).^4+(Tmin+273.16).^4)/2).*(.34-.14*sqrt(AVP)).*((1.35*Rmd./Rclearsky)-.35);
else
    Rnetlong = (4.903*10^-9)*(((Tmax+273.16).^4+(Tmin+273.16).^4)/2).*(.34-.14*sqrt(AVP)).*(1.35-.35);
end
Rnet = .408*(Rnetshort-Rnetlong);
```

Finally, we calculated the daily total ET. We did this by first calculating the solar radiation related ET, then the wind related ET. To make the calculations we used the delta term (DT), net radiation, psi Term (PT), temperature term (TT), actual vapor pressure (AVP), and mean saturation vapor pressure derived from air temperature.

```
ETrad = Delta_term.*Rnet;
ETwind = PT.*TT.*(Es-AVP);
ET=ETrad+ETwind;
```

Results:

Our model output each depth of straw into a separate excel file, each year was output on a seperate sheet. We then solved the average daily ET for each year at each depth and put it into a spreadsheet (Appendix 2, the full outputs would have been 1,600 pages and as a result we did not include them in the report). Using this data we made a scatterplot with each dept and year, with the dept as the independent variable, and the daily ET as the y (scatterplot with line of best fit in Appendix 3). After finding the line of best fit for the scatterplot, we then solved for the minimum price possible considering $.342 per inch per square meter, as the cost of the straw. Our initial run of the model did not work due to an error in the model. However after re running the model we solve it:

$$C_w = 0.17129452291(.2549x^2 - .8228x + 5.8991)$$

$$C_m = .03x$$

$$C = C_w + C_m$$

$$C = 0.17129452291(.2549x^2 - .8228x + 5.8991) + .03x$$

$$C' = \frac{d}{dx}[0.17129452291(.2549x^2 - .8228x + 5.8991) + .03x]$$

$$C' = 0$$

$$0 = \frac{d}{dx}[0.17129452291(.2549x^2 - .8228x + 5.8991) + .03x]$$

$$x = 1.27$$

At this optimum we estimate that the mulch could save $.012 per meter. Considering that the average farm in the US is 442 acres, this mulch could save more than 20,000 dollars each year.

Validation of Results:

We used weather data and followed exactly a guide to calculating ET, based on an equation that is the standard way to estimate ET. This standard was developed by a subset of the American Society of Civil Engineering. Furthermore, we validated albedo values by measuring the straw with color summarizers and a solar panel, where we could read the radiation that the surface was exposed to and the radiation reflected from the surface. As an albedo value is the reflected light divided by the exposed light we could validate the calculations.

Error Propagation:

There is some slight error in the albedo values starting at two inches. This is because at that point the color summarizer no longer detected the green in the paper backing, even though we could still see it in the pictures, however the change appears to be minimal. Furthermore, some years were missing a few days, however we still used them. This could have off put some of the declination related calculations. Additionally, our time frame was a little larger than the standard growing season (although some research suggests that organic mulch can increase the season), and our model did not account for mulch decay through the year. Further errors could exist in the wind related ET because of surface resistance changes.

Conclusions:

Based on our model and calculations the optimal depth of straw mulch in Taos New Mexico is 1.27 inches or 3.23 centimeters. At this mulch level farms would save 1.2 cents per square meter (including the cost of the mulch). This may seem like a small amount, however the average farm in the US is 442 acres and this would amount to about $49 per acre. This adds up to an estimated savings of 21,500 each year. This may be a little smaller due to the expense of mulching, however in addition to saving money in water, as we explained earlier, mulch can increase crop yield. Based on our research we believe that it is worth it for farmers to mulch their fields.

Recommendations:

Future research should be conducted taking wind into account. Furthermore, a more thorough model should be developed for the rates, including better data on the albedo values of the straw at any given depth, and the change in surface resistance. Further models should be made on mulches impact on rainwater retention. Additionally real world testing should be conducted on a similar system to see the total impact.

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Appendix 1

Δ	Slope of the vapor pressure curve
R_n	Net radiation
G	Soil heat flux density
γ	Psychometric constant
T	Mean daily temperature
u_2	Wind speed 2m above the ground
e_s	Saturation vapor pressure
e_a	Actual vapor pressure

Appendix 2

year\depth	0	0.25	0.5	0.75	1	1.25	1.5
1993	5.59963	5.39003	5.256119	5.098462	5.010667	4.995559	4.991634
1994	5.668103	5.449765	5.310272	5.146041	5.05459	5.038849	5.03476
1996	5.983123	5.765327	5.62618	5.462357	5.371133	5.35543	5.351352
1997	5.533629	5.312274	5.170853	5.004353	4.911638	4.895679	4.891533
1998	5.875893	5.657552	5.518057	5.35824	5.262372	5.24663	5.242542
1999	5.483746	5.272672	5.137819	4.979053	4.890644	4.875426	4.871474
2001	5.526907	5.292633	5.142958	4.96674	4.868614	4.851723	4.847336
2002	6.038861	5.810806	5.665103	5.493564	5.398042	5.3816	5.377329
2003	5.943586	5.716685	5.571721	5.401049	5.306011	5.289652	5.285403
2004	5.953043	5.734482	5.594846	5.430447	5.338903	5.323145	5.319052
2005	5.813156	5.587476	5.443291	5.273538	5.179012	5.162741	5.158515
2006	5.678448	5.449432	5.303116	5.130853	5.03493	5.018418	5.01413
2007	5.609517	5.381526	5.235865	5.064374	4.96888	4.952442	4.948173
2008	5.791515	5.57111	5.430295	5.264509	5.172192	5.156301	5.152173
2009	8.330345	8.209847	8.132861	8.042224	7.991753	7.983065	7.980809
2010	5.998662	5.774381	5.63109	5.46239	5.368449	5.352279	5.348079
2011	6.144107	5.921461	5.779216	5.611745	5.51849	5.502438	5.498268
2012	6.175012	5.94393	5.796295	5.622479	5.52569	5.50903	5.504702
2013	5.834006	5.612541	5.471049	5.030447	5.211706	5.195739	5.191592
2014	5.74716	5.527535	5.387219	5.22202	5.13003	5.114195	5.110082
2015	5.648831	5.422719	5.27826	5.108182	5.013475	4.997173	4.992939
2016	5.878372	5.654886	5.512103	5.344	5.250393	5.23428	5.230095
2017	5.854214	5.634369	5.493913	5.328549	5.236467	5.220617	5.2165

1.75	2	2.25	2.5	2.75	3
4.964944	4.945449	4.945449	4.945449	4.945449	4.945449
5.006957	4.986649	4.986649	4.986649	4.986649	4.986649
5.323617	5.30336	5.30336	5.30336	5.30336	5.30336
4.863346	4.842758	4.842758	4.842758	4.842758	4.842758
5.214738	5.19443	5.19443	5.19443	5.19443	5.19443
4.844595	4.824964	4.824964	4.824964	4.824964	4.824964
4.817503	4.795714	4.795714	4.795714	4.795714	4.795714
5.348288	5.327077	5.327077	5.327077	5.327077	5.327077
5.256509	5.235405	5.235405	5.235405	5.235405	5.235405
5.29122	5.270892	5.270892	5.270892	5.270892	5.270892
5.129777	5.108786	5.108786	5.108786	5.108786	5.108786
4.984967	4.963666	4.963666	4.963666	4.963666	4.963666
4.91914	4.897935	4.897935	4.897935	4.897935	4.897935
5.124107	5.103607	5.103607	5.103607	5.103607	5.103607
7.965464	7.954257	7.954257	7.954257	7.954257	7.954257
5.319519	5.298659	5.298659	5.298659	5.298659	5.298659
5.469916	5.449209	5.449209	5.449209	5.449209	5.449209
5.475276	5.453784	5.453784	5.453784	5.453784	5.453784
5.16339	5.142792	5.142792	5.142792	5.142792	5.142792
5.082115	5.061688	5.061688	5.061688	5.061688	5.061688

4.964146	4.943115	4.943115	4.943115	4.943115	4.943115
5.201636	5.180849	5.180849	5.180849	5.180849	5.180849
5.188505	5.168057	5.168057	5.168057	5.168057	5.168057

Appendix 3