

Appendix S3: Statistical Models, Results and Figures

This document lays out R code for all analyses and creates figures for “Climate and habitat continuity interact to alter contemporary dispersal potential”, by: Lauren L. Sullivan, Zoe M. Portlas, Kelsey M. Jaeger, Mercedes Hoffner, and Jill A. Hamilton (submitted 2023 to *Ecology*). Code was created by Lauren Sullivan, please contact LLSULL@msu.edu with questions.

```
library(plyr)
library(ggplot2)
library(lme4)
library(lmerTest)
library(lsmeans)
library(tidyverse)
library(MuMIn)
library(rootSolve)
library(pracma)
library(gridExtra)
library("cowplot")

##Data
gdat <- read.csv("geum_data.csv", header=TRUE) #trait and climate data
tvdat <- read.csv("terminalvelocity_data.csv", header=TRUE) #terminal velocity data
height <- read.csv("height_data.csv", header=TRUE) #flowering height data from herbaria
wind <- read.csv("wind_data.csv", header=TRUE) #wind data

#data clean
gdat$Replicate <- as.factor(gdat$Replicate) #rep per mom
```

#Data Analysis and Figure Creation

We first analyze all diaspore trait data and create the figures in the manuscript. We examine diaspore mass, morphology, and terminal velocity.

```
#####
#
#  MASS MEASUREMENTS
#
#####

##DIASPORE MASS
masstest <- lmer(sqrt(Weight_Tot) ~ Region * log(DD5_TOT) + (1|Population_Code) +
  (1|Year), data= gdat, REML=FALSE)
summary(masstest)

## Linear mixed model fit by maximum likelihood . t-tests use Satterthwaite's
## method [lmerModLmerTest]
## Formula: sqrt(Weight_Tot) ~ Region * log(DD5_TOT) + (1 | Population_Code) +
## (1 | Year)
## Data: gdat
##
```

```

##      AIC      BIC   logLik deviance df.resid
## -13191.0 -13151.9   6602.5 -13205.0     1977
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -4.1542 -0.6053  0.0175  0.6235  2.5967
##
## Random effects:
##   Groups             Name             Variance Std.Dev.
##   Population_Code (Intercept) 6.670e-05 0.008167
##   Year              (Intercept) 4.681e-05 0.006842
##   Residual                      6.395e-05 0.007997
## Number of obs: 1984, groups: Population_Code, 105; Year, 4
##
## Fixed effects:
##              Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)      0.15955    0.08574 103.41858   1.861   0.0656 .
## RegionPrairie     -0.23113    0.09916 103.15030  -2.331   0.0217 *
## log(DD5_TOT)       -0.01146    0.01129 103.35065  -1.015   0.3125
## RegionPrairie:log(DD5_TOT)  0.03073    0.01309 103.34316   2.347   0.0208 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##              (Intr) RgnPrr 1(DD5_
## RegionPrair -0.872
## lg(DD5_TOT) -0.999  0.873
## RP:(DD5_TOT  0.873 -1.000 -0.874

r.squaredGLMM(masstest)

##              R2m      R2c
## [1,] 0.04637078 0.6563381

#Set up color palatte for all figures
theme_ba <- function (base_size = 12, base_family = "")
{
  theme_grey(base_size = base_size, base_family = base_family) %+replace%
  theme(axis.text = element_text(size = rel(0.8)),
        axis.ticks = element_line(colour = "black"),
        legend.key = element_rect(colour = "grey80"),
        panel.background = element_rect(fill = "white",
        colour = NA), panel.border = element_rect(fill = NA,
        colour = "black"), panel.grid.major = element_line(colour = "white",
        size = 0.2), panel.grid.minor = element_line(colour = "white",
        size = 0.5), strip.background = element_rect(fill = "light grey",
        colour = "grey50", size = .75))
}

##Create Figure Panel 3a
mass <- ggplot(gdat, aes(x=log(DD5_TOT), y=sqrt(Weight_Tot), linetype = Region))+
  geom_point(aes(col=Region),size=3)+
  geom_point(shape=1,size=3,colour='black')+
  geom_smooth(aes(col=Region, fill = Region), method='lm', alpha = 1)+
  theme_ba()

```

```

    scale_color_manual(values=c('gray20','gray70'))+
    scale_fill_manual(values=c('gray40','gray40'))+
    scale_linetype_manual(values=c("dashed", "dashed"))+
    ylab('sqrt(Total Mass (mg))')+
    theme (legend.position="none" )+
    labs(tag = "A")+
    theme(axis.title.x=element_blank())

#####
#
#  MORPHOLOGY MEASUREMENTS
#
#####

##TOTAL DIASPORE LENGTH
lengthtest <- lmer(sqrt(Dispersal_and_seed_mm) ~ Region * log(DD5_TOT) +
                    (1|Population_Code/Sample_ID) + (1|Year), data = gdat, REML=FALSE)
summary(lengthtest)

## Linear mixed model fit by maximum likelihood . t-tests use Satterthwaite's
## method [lmerModLmerTest]
## Formula:
## sqrt(Dispersal_and_seed_mm) ~ Region * log(DD5_TOT) + (1 | Population_Code/Sample_ID) +
## (1 | Year)
## Data: gdat
##
##      AIC      BIC   logLik deviance df.resid
##  4435.0   4479.7  -2209.5   4419.0     1975
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -5.3336 -0.3884  0.0486  0.4242  3.6753
##
## Random effects:
##   Groups                Name      Variance Std.Dev.
## Sample_ID:Population_Code (Intercept) 0.3041   0.5515
## Population_Code           (Intercept) 0.4920   0.7014
## Year                      (Intercept) 0.2940   0.5422
## Residual                  0.2849   0.5337
## Number of obs: 1983, groups:
## Sample_ID:Population_Code, 1058; Population_Code, 105; Year, 4
##
## Fixed effects:
##              Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)      13.5825     7.5042 100.7621   1.810  0.07328 .
## RegionPrairie     -26.8529     8.6734 100.1707  -3.096  0.00254 **
## log(DD5_TOT)       -0.9270     0.9884 100.7644  -0.938  0.35056
## RegionPrairie:log(DD5_TOT)  3.5425     1.1452 100.3775   3.093  0.00256 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##              (Intr) RgnPrr 1(DD5_

```

```

## RegionPrair -0.872
## lg(DD5_TOT) -0.999 0.872
## RP:(DD5_TOT 0.873 -1.000 -0.874

r.squaredGLMM(lengthtest)

##          R2m          R2c
## [1,] 0.0773782 0.8088472

##DIASPORE AREA
areatest <- lmer(sqrt(SeedArea) ~ Region + log(DD5_TOT) + (1|Population_Code/Sample_ID) +
  (1|Year), data = gdat, REML=FALSE)
#summary(areatest)
#r.squaredGLMM(areatest)

##DIASPORE SHAPE INDEX
shapetest <- lmer(sqrt(SeedShapeIndex) ~ Region + log(DD5_TOT) +
  (1|Population_Code/Sample_ID) + (1|Year), data = gdat, REML=FALSE)
#summary(shapetest)
#r.squaredGLMM(shapetest)

##Create Figure Panel 3b
lnth <- ggplot(gdat, aes(x=log(DD5_TOT), y=sqrt(Dispersal_and_seed_mm),
  col=Region, linetype = Region))+
  geom_point(aes(col=Region),size=3)+
  geom_point(shape=1,size=3,colour='black')+
  geom_smooth(aes(col=Region, fill = Region),method='lm', alpha = 1)+
  theme_ba()+
  scale_color_manual(values=c('gray20','gray70'))+
  scale_fill_manual(values=c('gray40','gray40'))+
  scale_linetype_manual(values=c("dashed", "dashed"))+
  ylab('sqrt(Total Length (mm))')+
  theme (legend.position="none" )+
  labs(tag = "B")+
  theme(axis.title.x=element_blank())

#####
#
#  TERMINAL VELOCITY MEASUREMENTS
#
#####

##TERMINAL VELOCITY
tvtest <- lmer(sqrt(tv) ~ Region * log(DD5_TOT) + (1|Population/Sample_ID) + (1|Year),
  data=tvdat, REML=FALSE)
summary(tvtest)

## Linear mixed model fit by maximum likelihood . t-tests use Satterthwaite's
## method [lmerModLmerTest]
## Formula: sqrt(tv) ~ Region * log(DD5_TOT) + (1 | Population/Sample_ID) +
## (1 | Year)
## Data: tvdat

```

```
##
##      AIC      BIC    logLik deviance df.resid
## -1660.3 -1621.2    838.1 -1676.3      966
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -3.2857 -0.5438  0.0165  0.5834  4.9745
##
## Random effects:
## Groups              Name             Variance Std.Dev.
## Sample_ID:Population (Intercept) 0.0035682 0.05973
## Population           (Intercept) 0.0036991 0.06082
## Year                 (Intercept) 0.0007076 0.02660
## Residual                        0.0076454 0.08744
## Number of obs: 974, groups: Sample_ID:Population, 210; Population, 43; Year, 2
##
## Fixed effects:
##              Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)      0.06491    0.75664  42.94629   0.086  0.93203
## RegionPrairie      2.91763    0.98306  41.14790   2.968  0.00498 **
## log(DD5_TOT)       0.11313    0.09993  42.96562   1.132  0.26391
## RegionPrairie:log(DD5_TOT) -0.37984    0.12967  41.21754  -2.929  0.00552 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##              (Intr) RgnPrr l(DD5_
## RegionPrair -0.739
## lg(DD5_TOT) -0.999  0.737
## RP:(DD5_TOT  0.740 -1.000 -0.740

r.squaredGLMM(tvtest)

##              R2m      R2c
## [1,] 0.08930447 0.5542548

##Creates Figure Panel 3c
tv <- ggplot(tvdat, aes(x=log(DD5_TOT), y=sqrt(tv),
                        col=Region, linetype = Region))+
  geom_point(aes(col=Region),size=3)+
  geom_point(shape=1,size=3,colour='black')+
  geom_smooth(aes(col=Region, fill = Region),method='lm', alpha = 1)+
  theme_ba()+
  scale_color_manual(values=c('gray20','gray70'))+
  scale_fill_manual(values=c('gray40','gray40'))+
  scale_linetype_manual(values=c("dashed", "dashed"))+
  ylab('sqrt(Terminal Velocity (m/s))')+
  theme(legend.position="none")+
  labs(tag = "C")+
  theme(axis.title.x=element_blank())

#to make the legend readable.
leg <- ggplot(tvdat, aes(x=log(DD5_TOT), y=sqrt(tv),col=Region))+
  geom_point(aes(col=Region),size=3, position = position_dodge(width = 0.1))+
  scale_color_manual(values=c('gray20','gray70'))+
```

```

theme_bw()

g_legend<-function(a.gplot){
  tmp <- ggplot_gtable(ggplot_build(a.gplot))
  leg <- which(sapply(tmp$grobs, function(x) x$name) == "guide-box")
  legend <- tmp$grobs[[leg]]
  return(legend)}

mylegend<-g_legend(leg)

##Creates Figure 3
Fig3_a <- plot_grid(mass, lnth, tv,
                    nrow = 1)

## `geom_smooth()` using formula = 'y ~ x'
## `geom_smooth()` using formula = 'y ~ x'
## `geom_smooth()` using formula = 'y ~ x'

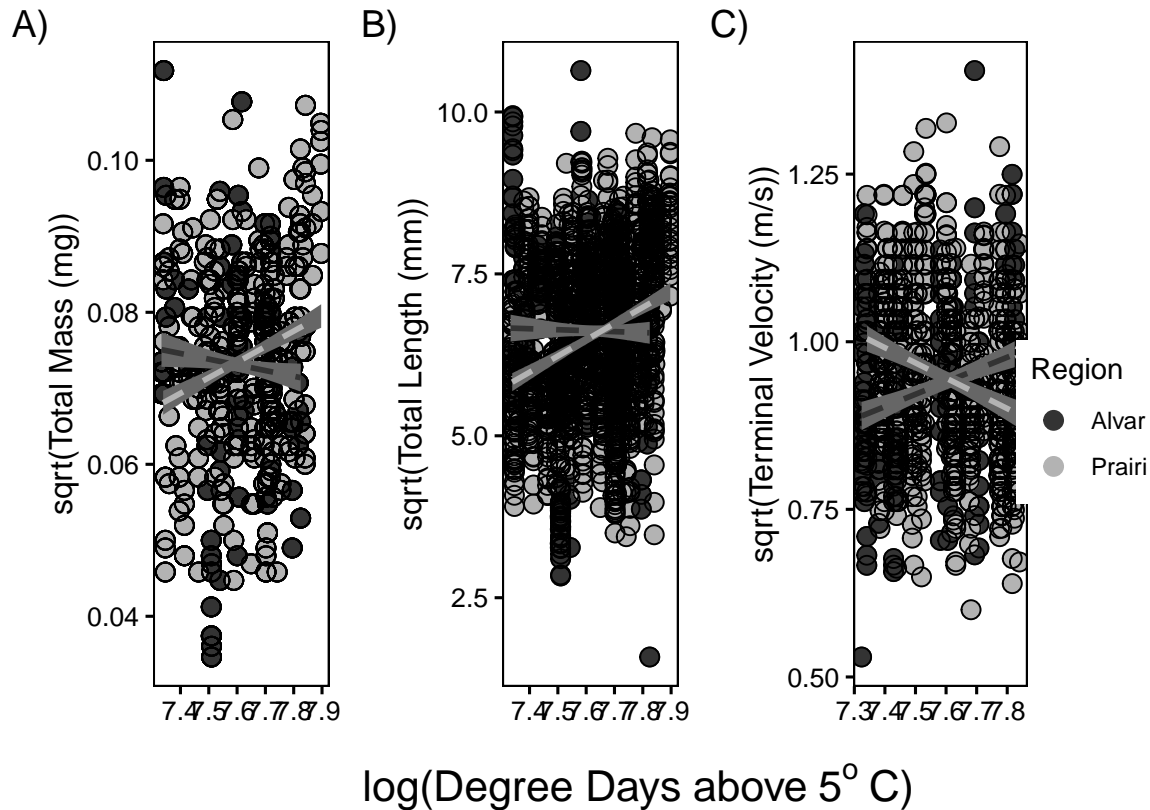
title_x <- ggdraw()+
  draw_label(bquote('log(Degree Days above' ~5^o~C*')'),
             fontface = "bold",
             x = .35, y = .9,
             hjust = 0,
             size = 16)

Fig3_b <- plot_grid(Fig3_a, NULL, title_x,
                    ncol = 1,
                    rel_heights = c(1,0.05, 0.1))

Fig3_all <- plot_grid(Fig3_b, mylegend,
                     rel_widths = c(10,1),
                     nrow = 1)

Fig3_all

```



```
# tiff("Fig3.tiff", units="in", width=8.5, height=4, res=300, compression = 'lzw')
# Fig3_all
# dev.off()
```

Next we take the terminal velocity data and translate it into a dispersal potential ability at the 99% tail of the dispersal kernel.

```
## Examine height differences by region
summary(aov(height_cm ~ Region, data = height))

##           Df Sum Sq Mean Sq F value Pr(>F)
## Region      1   17.4    17.38   0.461  0.499
## Residuals  83 3131.3    37.73

##Translate TV into max dispersal

height_avg <- ddply(height, .(Region), summarize, avg_flwr_ht = mean(height_cm)/100)
wind_avg <- ddply(wind, .(measurement), summarize, wind_average =
  (mean(value)*1000)/3600) #km/h into m/s

height_avg$max_wind <- 0
height_avg$equal_wind <- 0
height_avg[2,3] <- wind_avg[2,2] #add prairie wind - which is avg of June winds at
# Geum common garden for 2017 and 2018
height_avg[1,3] <- wind_avg[2,2]/2 #assume alvar wind is 50% of prairie wind
height_avg[4,4] <- wind_avg[2,2] #for equal wind between prairie and alvar.

tvdat_all <- merge(tvdat, height_avg, by="Region")
```

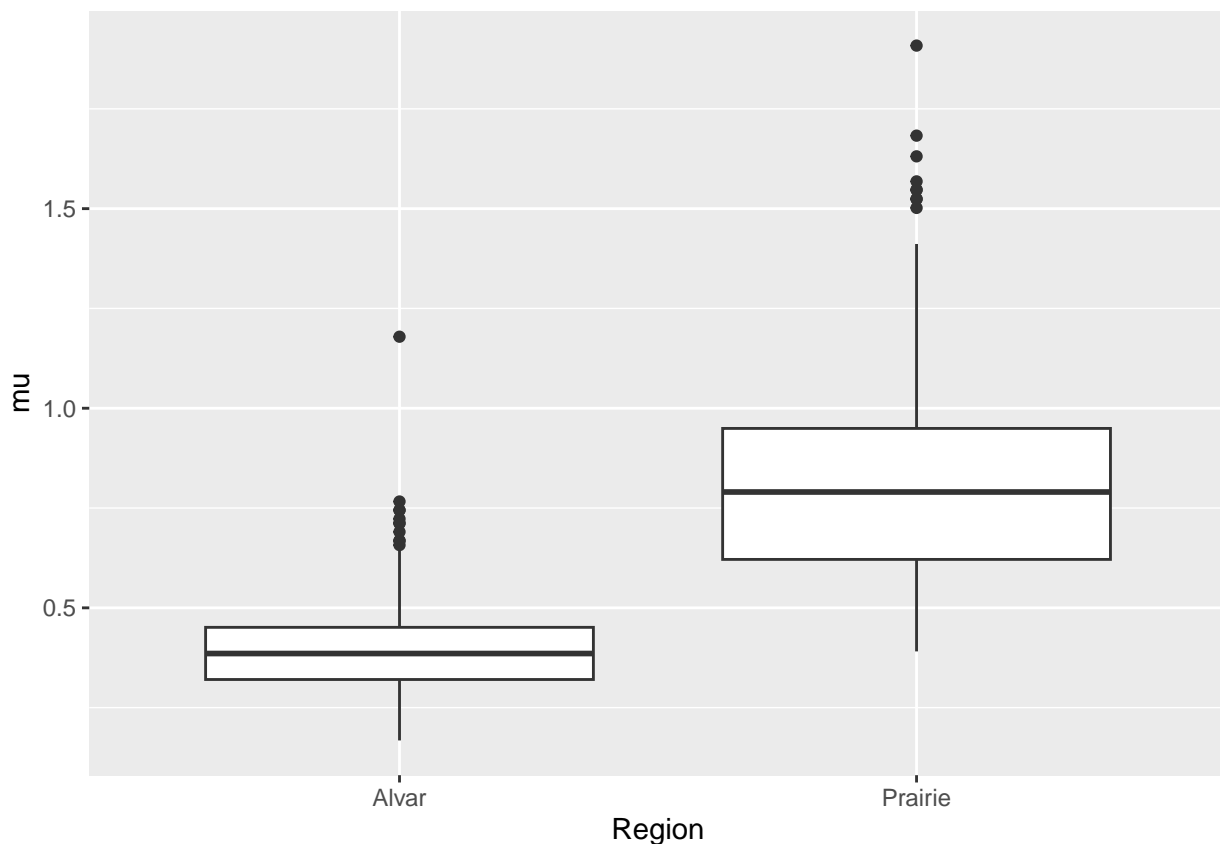
```

##Creating the kernels using the WALD model (based on Katul et al. 2005)
#Wind-based, and other non-plant parameters
kappa <- .3      #set between .3 and .4; (.3 = canopies that are very dense)
h <- .2          #Canopy height.
sigma2 <- kappa*h*(2*(1/2)) #sigma2 <- kappa*h*(2*(sigmaw/U)) - sigmaw/U = ratio of 1/2.
g <- 9.8 #m/s
rho <- .001225*1000000 #g/m3, density of air at 15oC at sea level is 0.001225 g/cm3

#Inverse-gaussian params (WALD), calculated from data and wind parameters
tvdat_all$lambda <- (tvdat_all$avg_flwr_ht/sqrt(sigma2))^2 #lambda
tvdat_all$mu <- (tvdat_all$avg_flwr_ht*tvdat_all$max_wind)/tvdat_all$tv #mu

#plot exploring mean dispersal distance by region
ggplot(tvdat_all, aes(x=Region, y=mu))+
  geom_boxplot()

```



```

#Use CDF to extract tail, or the distance the farthest 1% will travel.
results_dstar <- matrix(nrow=0,ncol=2)
row <- as.vector(1:nrow(tvdat_all))
max_tail <- 10000

for(i in 1:length(row)){
  #i=3
  temp <- tvdat_all[i,]
  lambda <- temp$lambda
  mu <- temp$mu

```



```

fun_99<- function(x) (.5*erfc((sqrt(lambda/x)*(mu-x))/(sqrt(2)*mu)) +
.5*(exp((2*lambda)/mu))*erfc((sqrt(lambda/x)*(mu+x))/(sqrt(2)*mu))-.99)
dstar_99 <- uniroot(fun_99, c(.00001,max_tail))$root

new <- cbind(temp, dstar_99)
results_dstar <- rbind(results_dstar, new)

#print(i/length(row)) #keeps track of progress
}

#write_csv(results_dstar, "GEUM_dispersal_kernel_integration.csv")

##DISPERSAL POTENTIAL
disp99_test <- lmer((dstar_99) ~ Region * log(DD5_TOT) + (1|Population/Sample_ID) +
(1|Year), data=results_dstar, REML=FALSE)
summary(disp99_test)

## Linear mixed model fit by maximum likelihood . t-tests use Satterthwaite's
## method [lmerModLmerTest]
## Formula: (dstar_99) ~ Region * log(DD5_TOT) + (1 | Population/Sample_ID) +
## (1 | Year)
## Data: results_dstar
##
##      AIC      BIC   logLik deviance df.resid
## 2641.5   2680.5  -1312.7   2625.5     966
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.9823 -0.4352 -0.1124  0.2675  8.0772
##
## Random effects:
## Groups              Name            Variance Std.Dev.
## Sample_ID:Population (Intercept) 0.1792   0.4234
## Population           (Intercept) 0.2424   0.4924
## Year                 (Intercept) 0.0356   0.1887
## Residual                        0.6821   0.8259
## Number of obs: 974, groups: Sample_ID:Population, 210; Population, 43; Year, 2
##
## Fixed effects:
##              Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)      3.3730     6.0790  43.3025   0.555   0.5818
## RegionPrairie    -18.9393     7.9174  41.2638  -2.392   0.0214 *
## log(DD5_TOT)      -0.2794     0.8028  43.3295  -0.348   0.7295
## RegionPrairie:log(DD5_TOT)  2.7365     1.0443  41.3439   2.620   0.0122 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##      (Intr) RgnPrr l(DD5_
## RegionPrair -0.739
## lg(DD5_TOT) -0.999  0.738
## RP:(DD5_TOT  0.741 -1.000 -0.740

```

```
r.squaredGLMM(disp99_test)
```

```
##           R2m           R2c
## [1,] 0.4324425 0.6602234
```

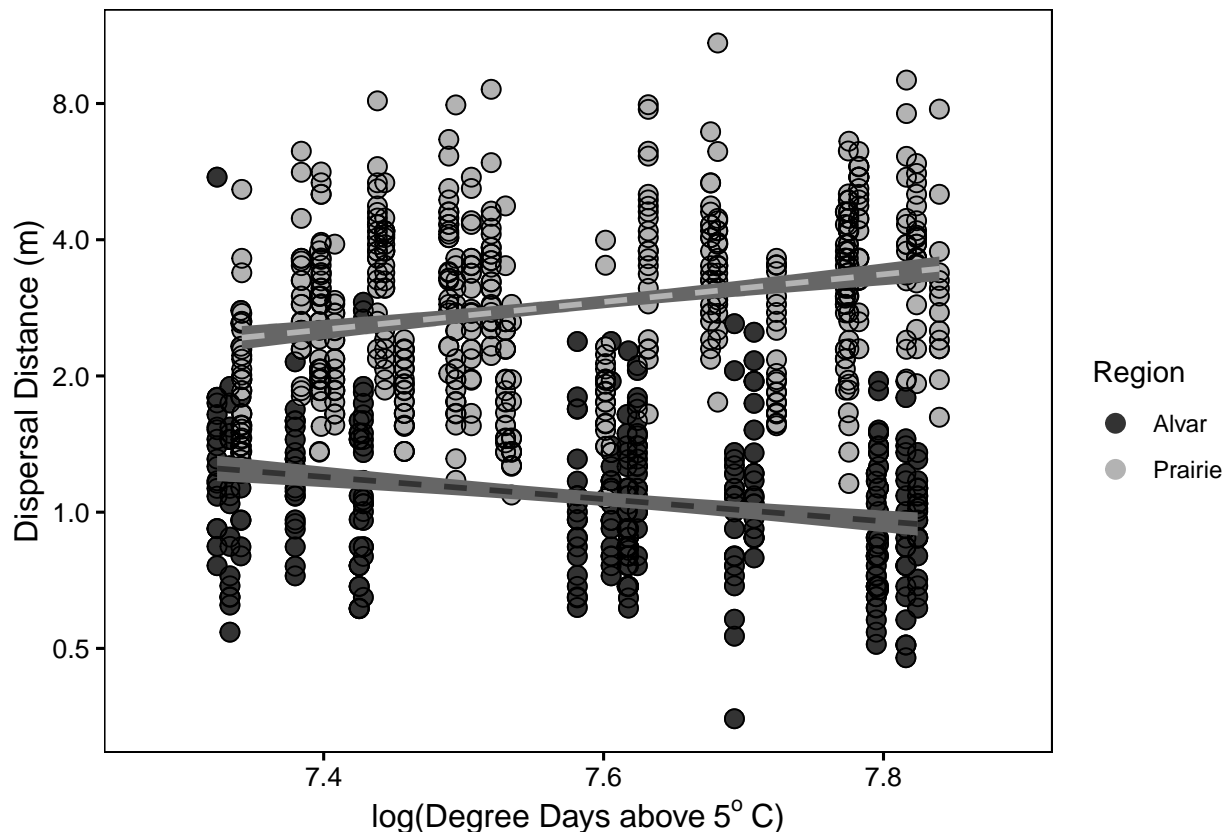
```
##Creates Figure 4
```

```
Fig4_a <- ggplot(results_dstar, aes(x=log(DD5_TOT), y=dstar_99,col=Region,
                                   linetype = Region))+
  geom_point(aes(col=Region),size=3, position = position_dodge(width = 0.1))+
  geom_point(shape=1,size=3,colour='black', position = position_dodge(width = 0.1))+
  geom_smooth(aes(col=Region, fill = Region),method='lm', alpha = 1)+
  theme_ba()+
  scale_color_manual(values=c('gray20','gray70'))+
  scale_fill_manual(values=c('gray40','gray40'))+
  scale_linetype_manual(values=c("dashed", "dashed"))+
  xlab(bquote('log(Degree Days above' ~5^o-C*')))+
  ylab('Dispersal Distance (m)')+
  theme (legend.position="none" )+
  scale_y_continuous(trans = 'log2')
```

```
Fig4_all <- plot_grid(Fig4_a, mylegend,
                      rel_widths = c(3,0.5),
                      nrow = 1)
```

```
## `geom_smooth()` using formula = 'y ~ x'
```

```
Fig4_all
```



```
# tiff("Fig4.tiff", units="in", width=5, height=4, res=300, compression = 'lzw')  
# Fig4_all  
# dev.off()
```