Analysis

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Preparing Data

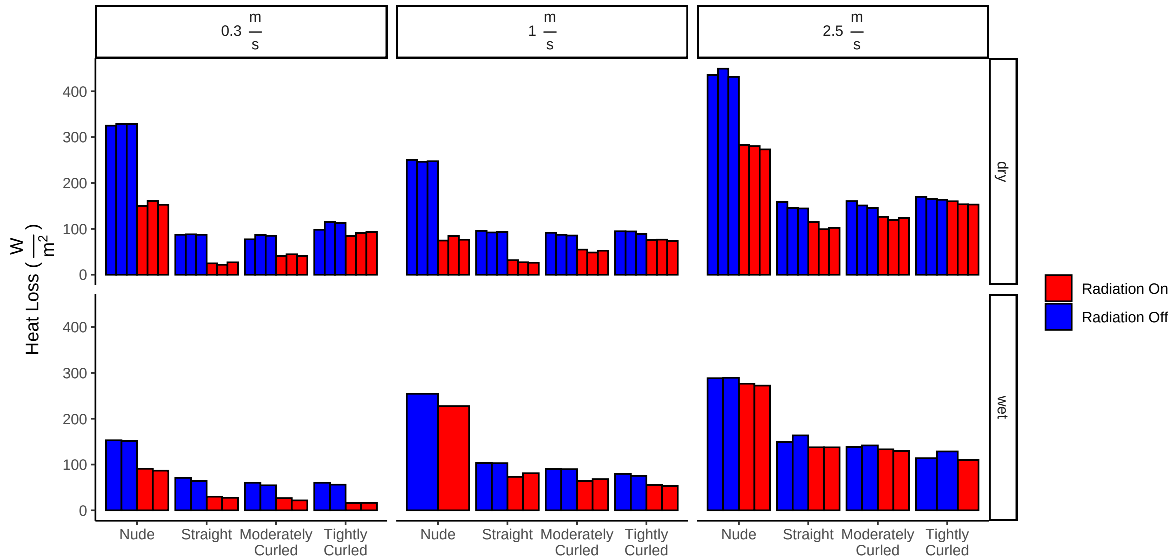
First, we import the data and label the variables.

Data preview

```
# Preview data
head(df_wetdry) %>%
    kbl(booktabs = T) %>%
    kable_styling(latex_options = c("striped", "scale_down"))
```

wind	wig	wet_dry	heat_loss	skin_temp	resistance	clo	amb_temp	amb_rh	radiation	trial
0.3	Nude	wet	90.87576	34.01121	0.0000000	0.0000003	34.01091	45.81515	on	1
0.3	Nude	wet	86.74872	34.01205	-0.0012118	-0.0078183	34.11821	45.77179	on	2
1.0	Nude	wet	227.27600	34.02600	0.0001190	0.0007674	33.99840	46.25600	on	1
2.5	Nude	wet	276.44615	34.02462	-0.0008197	-0.0052881	34.25051	48.20513	on	1
2.5	Nude	wet	272.29630	34.01741	-0.0008039	-0.0051862	34.23296	48.12963	on	2
0.3	Straight	wet	30.00323	34.00065	-0.0042217	-0.0272367	34.12710	45.43548	on	1

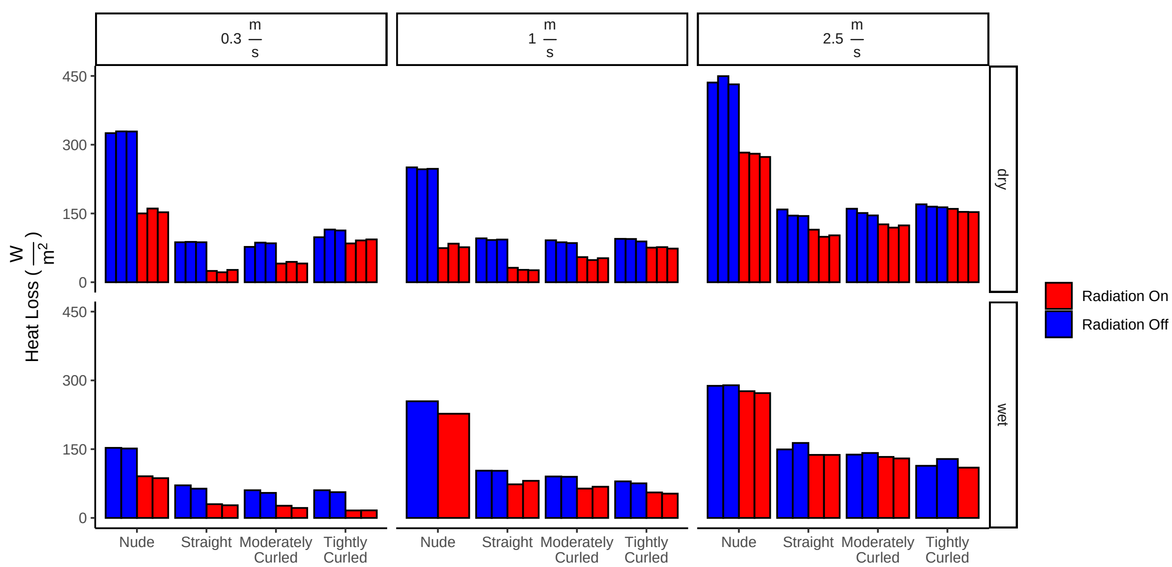
Plots



Removing Outlier

It was noticed that the 2nd trial conducted with wet, tightly curled hair, 2.5 m/s wind speed, and radiation on, had more heat loss than any of the trials with radiation off. With the understanding that radiation should always decrease heat loss, we elected to remove that data point.

```
# Remove specific entry
df_wetdry <- df_wetdry %>%
    filter(!(wig == "Tightly\nCurled" & wind == 2.5 & radiation ==
        "on" & wet_dry == "wet" & trial == "1"))
```



Regression models

Radiation off

Here, we model the effect of the `wig` variable on the `off` (heat loss without radiation) variable while correcting for `wind`.

Without radiation, having hair will reduce the heat loss.

```
##
## Call:
## lm(formula = off ~ wind + wig, data = df_dry_off)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -8.0303 -3.9809  0.1861  2.6542 14.6310
##
## Coefficients:
##                        Estimate Std. Error t value Pr(>|t|)
## (Intercept)              46.156      2.250   20.52  < 2e-16 ***
## wind                     11.270      1.009   11.17 2.13e-12 ***
## wigStraight             -40.341      2.618  -15.41 4.46e-16 ***
## wigModerately\nCurled  -40.747      2.618  -15.56 3.38e-16 ***
## wigTightly\nCurled     -38.362      2.618  -14.65 1.76e-15 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 5.555 on 31 degrees of freedom
## Multiple R-squared:  0.9384, Adjusted R-squared:  0.9305
## F-statistic: 118.1 on 4 and 31 DF,  p-value: < 2.2e-16
```

Radiation on

With radiation, there is a net increase in heat (i.e. heat gain) without any hair. Additonally, we observe that heat gain decreases with increasingly curled hair.

```
##
## Call:
## lm(formula = on ~ wind + wig, data = df_dry_on)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -13.6776  -4.8542  -0.0306   3.3559  19.1058
##
## Coefficients:
##                        Estimate Std. Error t value Pr(>|t|)
## (Intercept)            -129.327      2.835  -45.61  < 2e-16 ***
## wind                     17.406      1.271   13.69  1.1e-14 ***
## wigStraight              69.844      3.300   21.16  < 2e-16 ***
## wigModerately\nCurled   91.558      3.300   27.74  < 2e-16 ***
## wigTightly\nCurled     113.668      3.300   34.44  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
##
## Residual standard error: 7.001 on 31 degrees of freedom
## Multiple R-squared:   0.98,  Adjusted R-squared:  0.9775
## F-statistic: 380.4 on 4 and 31 DF,  p-value: < 2.2e-16
```

Solar influx

Here, we model the effect of the `wig` variable on `influx` while correcting for `wind`.

In the dry heat loss experiments, we see that all hair (regardless of curliness) decreases the solar influx. Additionally, the curlier the hair, the lower the solar influx.

```
##
## Call:
## lm(formula = influx ~ wind + wig, data = df_dry)
##
## Residuals:
##    Min     1Q Median     3Q    Max
## -8.079 -3.816  1.087  2.763  9.105
##
## Coefficients:
##                          Estimate Std. Error t value Pr(>|t|)
## (Intercept)              175.4829     2.0133  87.161  < 2e-16 ***
## wind                      -6.1369     0.9028  -6.798 1.3e-07 ***
## wigStraight             -110.1848     2.3434 -47.019  < 2e-16 ***
## wigModerately\nCurled -132.3051     2.3434 -56.459  < 2e-16 ***
## wigTightly\nCurled    -152.0302     2.3434 -64.876  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 4.971 on 31 degrees of freedom
## Multiple R-squared:  0.9939, Adjusted R-squared:  0.9932
## F-statistic:  1272 on 4 and 31 DF,  p-value: < 2.2e-16
```

Summary of dry heat loss regression models

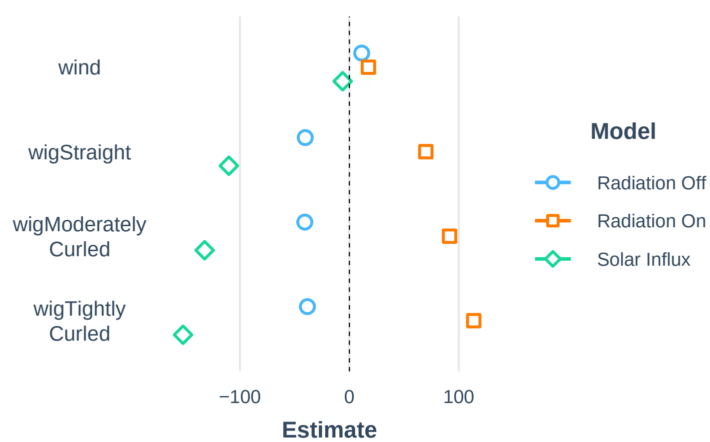


Figure 1: Regression coefficients across regression models.

	Radiation Off	Radiation On	Solar Influx
(Intercept)	46.16 ***	-129.33 ***	175.48 ***
	[41.57, 50.74]	[-135.11, -123.54]	[171.38, 179.59]
wind	11.27 ***	17.41 ***	-6.14 ***
	[9.21, 13.33]	[14.81, 20.00]	[-7.98, -4.30]
wigStraight	-40.34 ***	69.84 ***	-110.18 ***
	[-45.68, -35.00]	[63.11, 76.58]	[-114.96, -105.41]
wigModeratelyCurled	-40.75 ***	91.56 ***	-132.31 ***
	[-46.09, -35.41]	[84.83, 98.29]	[-137.08, -127.53]
wigTightlyCurled	-38.36 ***	113.67 ***	-152.03 ***
	[-43.70, -33.02]	[106.94, 120.40]	[-156.81, -147.25]
N	36	36	36
R2	0.94	0.98	0.99

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Dry heat loss ANOVA plots

Evaporative resistance (wet experiments)

Here, we repeat the same modelling process for the evaporative resistance data from the wet experiments.

Radiation off

Here, we model the effect of the `wig` variable on the `off` (heat loss without radiation) variable while correcting for `wind`.

Without solar radiation, all hair (regardless of texture) decreases evaporative resistance.

```
##
## Call:
## lm(formula = off ~ wind + wig, data = df_wet_off)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -32.382  -6.006   2.673   5.870  40.839
##
## Coefficients:
##                      Estimate Std. Error t value Pr(>|t|)
## (Intercept)           171.043      9.132   18.73 8.71e-13 ***
## wind                   42.585      3.929   10.84 4.69e-09 ***
## wigStraight          -116.024     10.179  -11.40 2.20e-09 ***
```

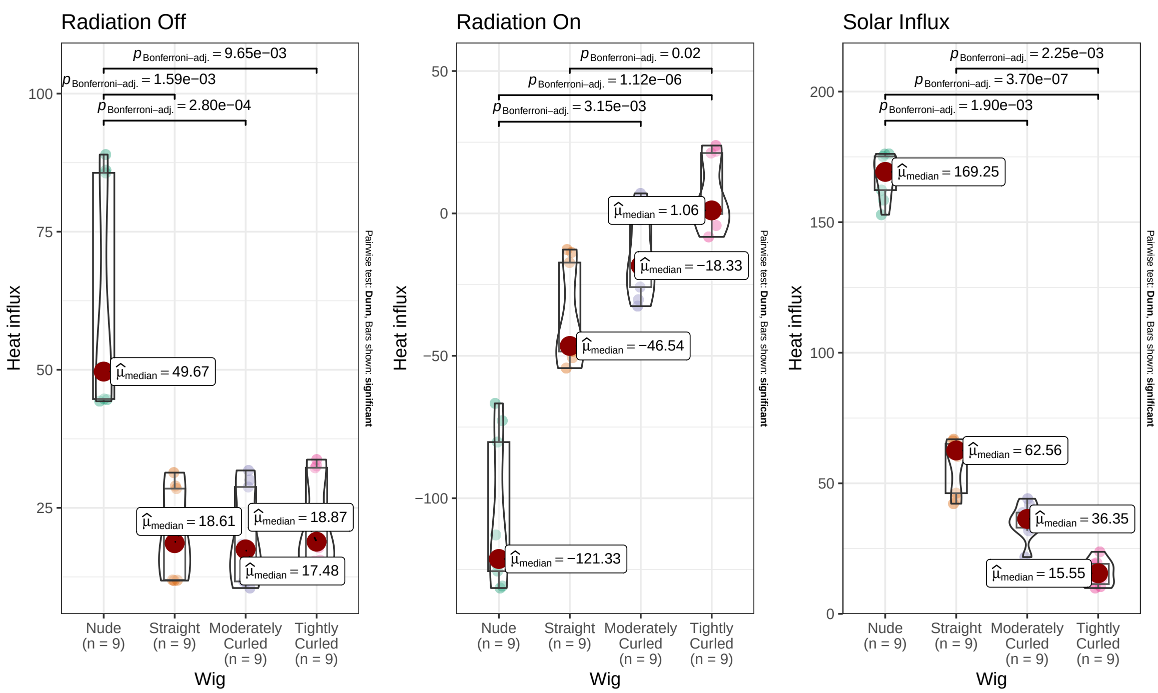


Figure 2: ANOVA of dry heat loss

```
## wigModerately\nCurled -129.170     10.179  -12.69 4.26e-10 ***
## wigTightly\nCurled    -134.409     10.695  -12.57 4.95e-10 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 16.81 on 17 degrees of freedom
## Multiple R-squared:  0.9551, Adjusted R-squared:  0.9446
## F-statistic: 90.46 on 4 and 17 DF,  p-value: 3.177e-11
```

Radiation on

With radiation, hair decreases evaporative resistance.

```
##
## Call:
## lm(formula = on ~ wind + wig, data = df_wet_on)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -47.426 -11.303   4.423   6.822  54.290
##
## Coefficients:
##                        Estimate Std. Error t value Pr(>|t|)
## (Intercept)             117.541     12.726   9.236 4.90e-08 ***
## wind                     55.445      5.475  10.127 1.29e-08 ***
## wigStraight            -106.632     14.186  -7.517 8.44e-07 ***
## wigModerately\nCurled -113.898     14.186  -8.029 3.48e-07 ***
```

```
## wigTightly\nCurled    -123.891     14.905  -8.312 2.16e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 23.42 on 17 degrees of freedom
## Multiple R-squared:  0.9255, Adjusted R-squared:  0.908
## F-statistic:  52.8 on 4 and 17 DF,  p-value: 2.297e-09
```

Solar influx

Combining the above data to calculate solar influx, we see that there is not a considerable effect of radiation on evaporative resistance.

```
##
## Call:
## lm(formula = influx ~ wind + wig, data = df_wet)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -13.4512  -4.2205  -0.7951   3.9758  15.0438
##
## Coefficients:
##                       Estimate Std. Error t value Pr(>|t|)
## (Intercept)             53.502      4.585  11.669 1.54e-09 ***
## wind                   -12.860      1.973  -6.520 5.24e-06 ***
## wigStraight             -9.392      5.111  -1.838  0.08368 .
## wigModerately\nCurled  -15.272      5.111  -2.988  0.00826 **
## wigTightly\nCurled     -10.518      5.370  -1.959  0.06676 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 8.439 on 17 degrees of freedom
## Multiple R-squared:  0.7493, Adjusted R-squared:  0.6903
## F-statistic:  12.7 on 4 and 17 DF,  p-value: 5.753e-05
```

Summary of evaporative heat loss regression models

Evaporative heat ANOVA plots

Calculating Thermal Resistance

$$I_t = \frac{T_{Skin} - T_{Air}}{H_{Dry}}$$

```
df_wetdry["dry_heat_resistance"] <- (df_wetdry["skin_temp"] -
    df_wetdry["amb_temp"])/df_wetdry["heat_loss"]

# For the dry data, leave this blank
df_wetdry <- df_wetdry %>%
    mutate(dry_heat_resistance = ifelse(wet_dry == "wet",
        NaN, dry_heat_resistance))
```

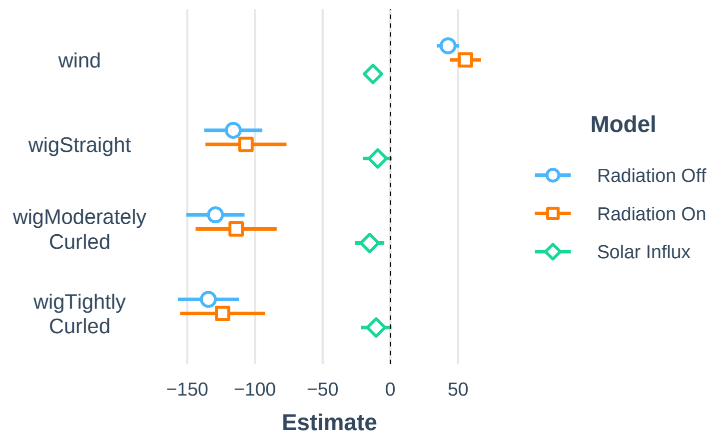


Figure 3: Regression coefficients across regression models.

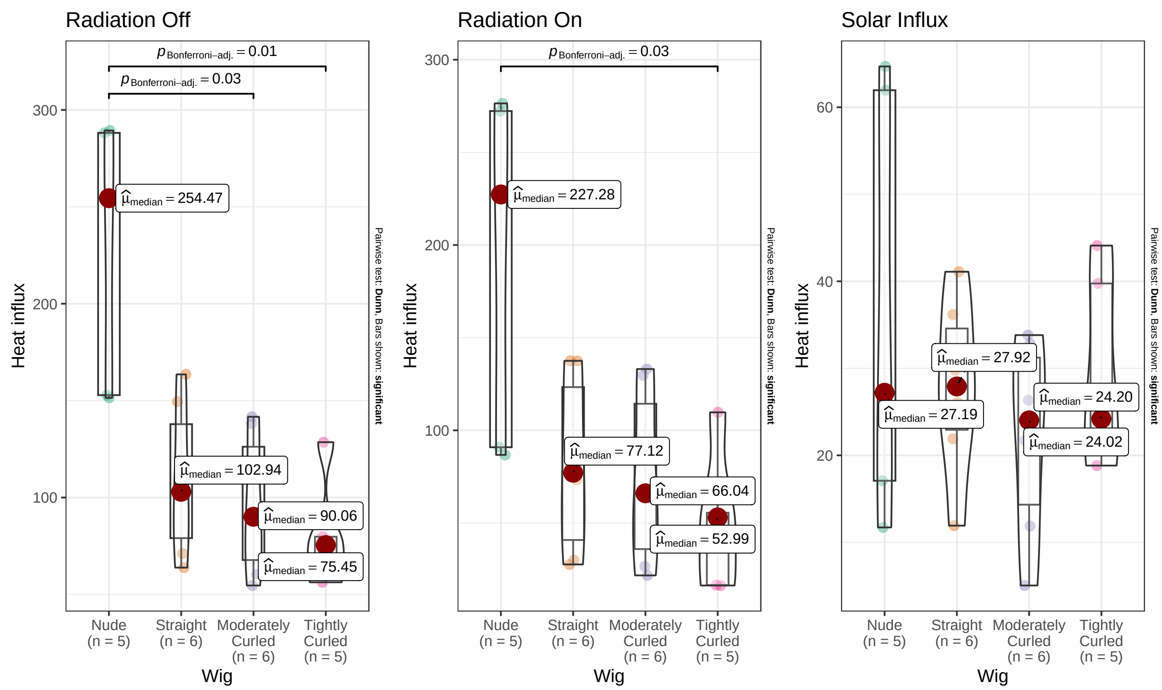
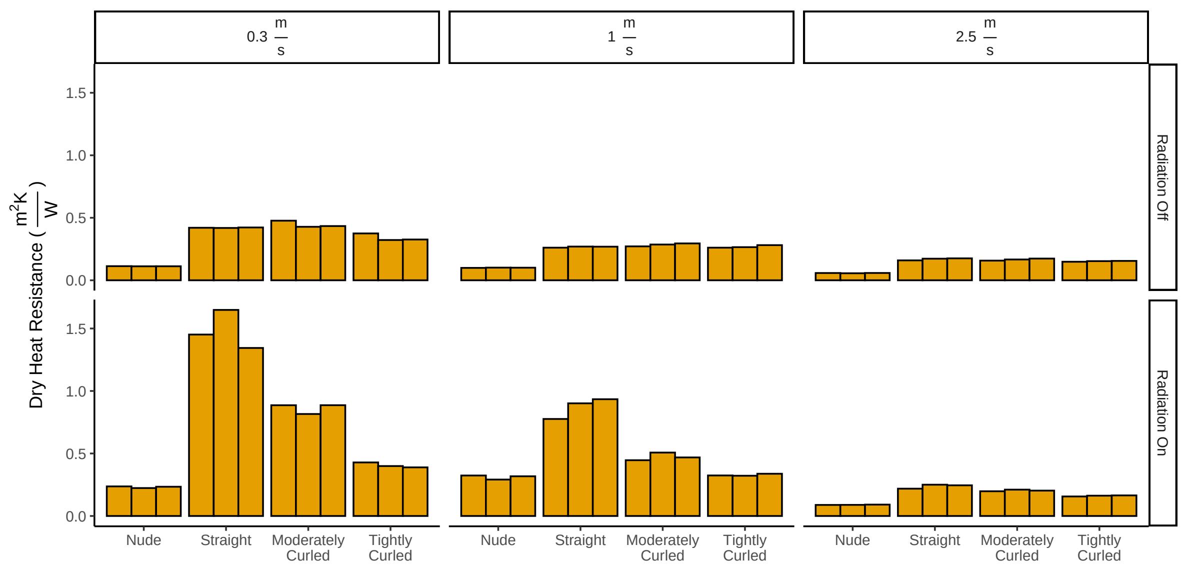


Figure 4: ANOVA of evaporative heat loss

	Radiation Off	Radiation On	Solar Influx
(Intercept)	171.04 ***	117.54 ***	53.50 ***
	[151.78, 190.31]	[90.69, 144.39]	[43.83, 63.18]
wind	42.58 ***	55.44 ***	-12.86 ***
	[34.30, 50.87]	[43.89, 67.00]	[-17.02, -8.70]
wigStraight	-116.02 ***	-106.63 ***	-9.39
	[-137.50, -94.55]	[-136.56, -76.70]	[-20.17, 1.39]
wigModeratelyCurled	-129.17 ***	-113.90 ***	-15.27 **
	[-150.65, -107.69]	[-143.83, -83.97]	[-26.06, -4.49]
wigTightlyCurled	-134.41 ***	-123.89 ***	-10.52
	[-156.97, -111.84]	[-155.34, -92.45]	[-21.85, 0.81]
N	22	22	22
R2	0.96	0.93	0.75

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

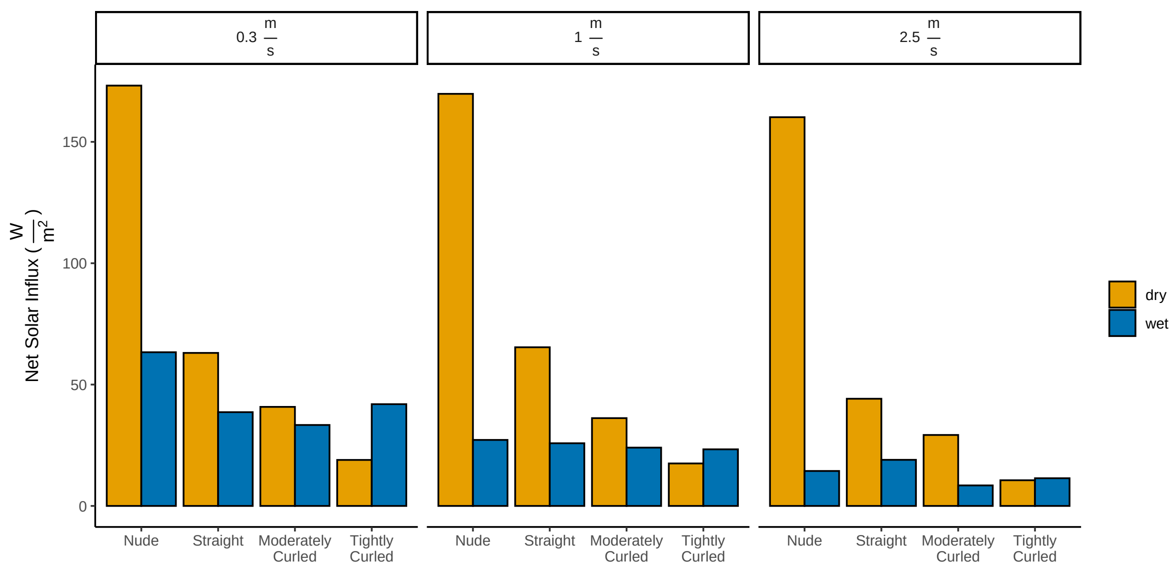


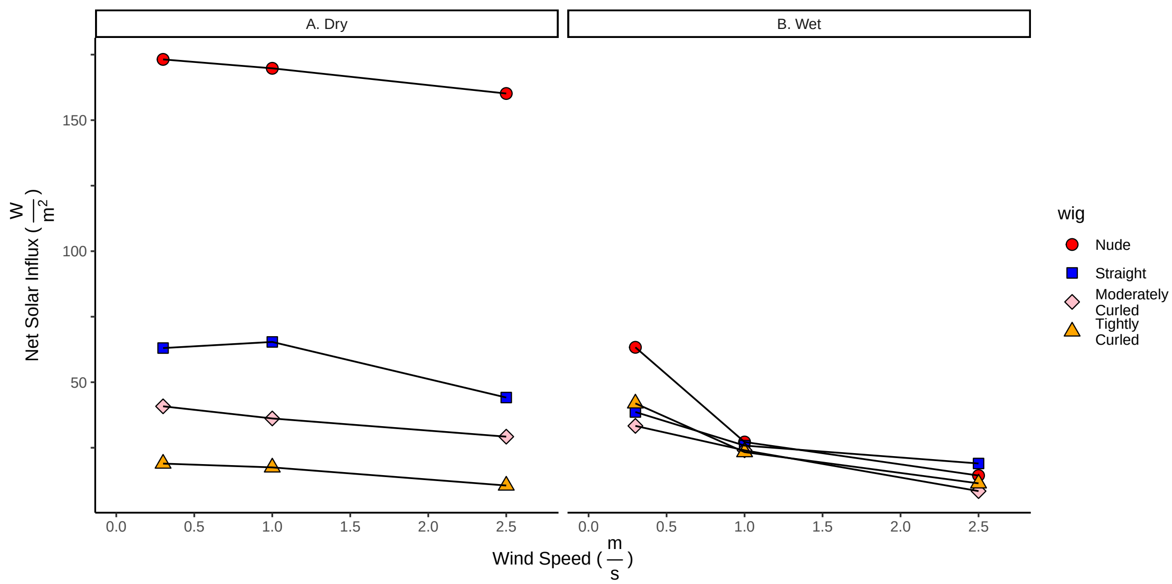
Calculating Net Solar Influx

$$I_{Dry} = H_{Dry} - H_{Dry}^{Solar}$$

$$I_{Evap} = H_{Evap} - H_{Evap}^{Solar}$$

```r
# Average all trials with the same characteristics
df_averaged_trials <- df_wetdry %>%
    group_by(wig, wind, radiation, wet_dry) %>%
    drop_na(heat_loss) %>%
    summarise(heat_loss = mean(heat_loss))

# Pivot the dataframe to incldue radiation on and off
# as part of same event
df_radiation_split <- df_averaged_trials %>%
    pivot_wider(names_from = c(radiation), values_from = c(heat_loss)) %>%
    rename(heat_loss_off = off) %>%
    rename(heat_loss_on = on)

# Calculate the net influx
df_net_influx_plots <- df_radiation_split %>%
    group_by(wig, wind) %>%
    summarise(wet_dry = wet_dry, net_influx = heat_loss_off -
        heat_loss_on)

df_net_influx <- df_net_influx_plots %>%
    spread(wet_dry, net_influx)
```





Adjusting Heat Losses to 30 Degrees Celsius

Dry Heat Loss

$$H_{Dry}^{30^\circ C} = \frac{35 - 30}{I_t}$$

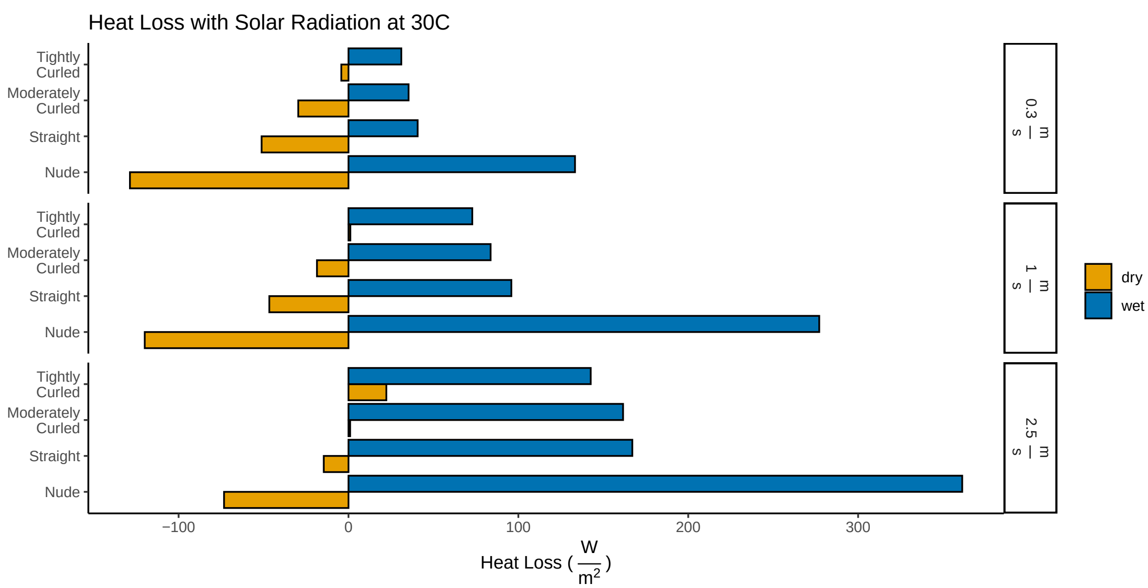
```
# Their calculation
df_wetdry["heat_30"] = (35 - 30)/df_wetdry["dry_heat_resistance"]

# What I would expect df_wetdry['heat_30'] =
# (df_wetdry['skin_temp'] - 30) /
# df_wetdry['dry_heat_resistance']


# Recreate the radiation split dataframe to include
# heat_30
df_averaged_trials <- df_wetdry %>%
    group_by(wig, wind, radiation, wet_dry) %>%
    drop_na(heat_loss) %>%
    summarise(heat_loss = mean(heat_loss), heat_30 = mean(heat_30))

df_radiation_split <- df_averaged_trials %>%
    pivot_wider(names_from = c(radiation), values_from = c(heat_loss,
        heat_30))
```

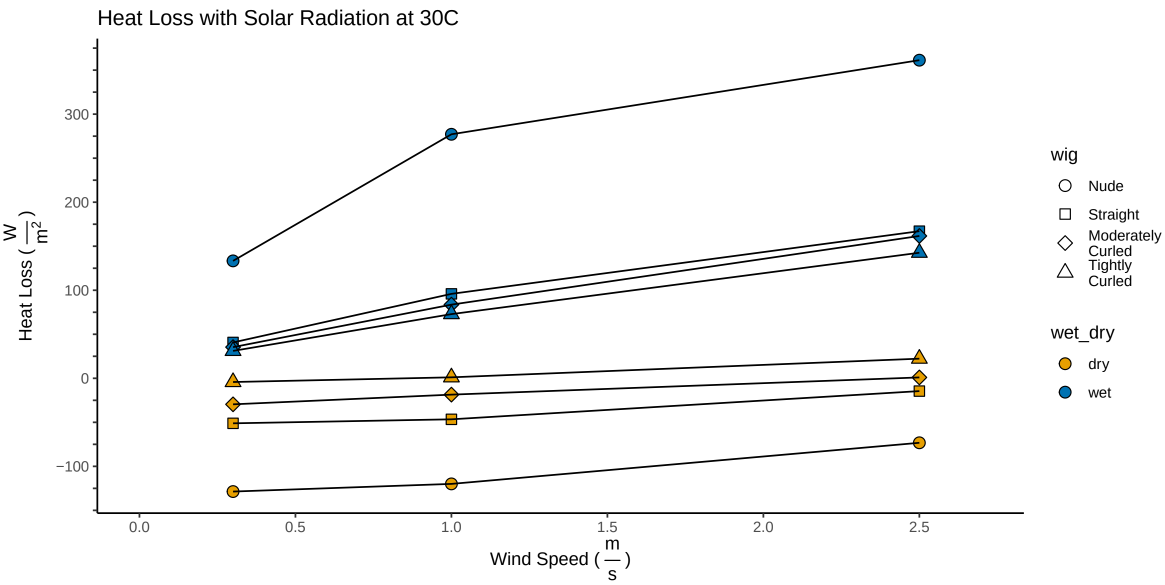
Dry and Wet Heat Losses With Solar Radiation

$$H_{Dry}^{30^\circ C,\, Solar} = H_{Dry}^{30^\circ C} - I_{Dry}$$

$$H_{Wet}^{30^\circ C,\, Solar} = H_{Evap+Dry}^{30^\circ C} = H_{Evap} + I_{Dry} + H_{Dry}^{30^\circ C,\, Solar}$$

```r
dry_heat_30 = df_radiation_split[df_radiation_split$wet_dry ==
    "dry", ]

heat_evap = df_radiation_split[df_radiation_split$wet_dry ==
    "wet", ]


df_adjusted_solar <- data.frame(dry_heat_loss <- dry_heat_30$heat_30_off -
    df_net_influx$dry, wind <- dry_heat_30$wind, wig <- dry_heat_30$wig) %>%
    rename(dry_heat_loss = "dry_heat_loss....dry_heat_30.heat_30_off...df_net_influx.dry") %>%
    rename(wind = "wind....dry_heat_30.wind") %>%
    rename(wig = "wig....dry_heat_30.wig")


df_adjusted_solar["wet_heat_loss"] <- +heat_evap$heat_loss_on +
    df_net_influx$dry + df_adjusted_solar$dry_heat_loss


df_adjusted_solar_plots <- df_adjusted_solar %>%
    pivot_longer(cols = c("dry_heat_loss", "wet_heat_loss"),
        names_to = "wet_dry", values_to = "heat_loss")
```





Calculating Evaporative Potential

$$H_{Max}^{30^\circ C,\ Solar} = H_{Wet}^{30^\circ C,\ Solar} - H_{Dry}^{30^\circ C,\ Solar}$$

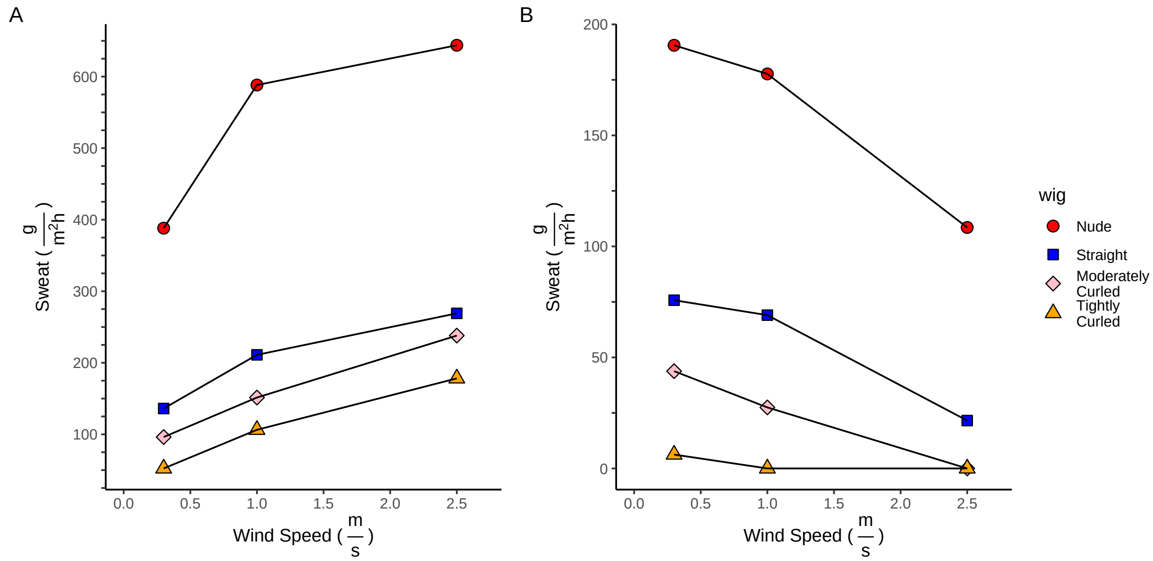
```
df_evaporative_potential <- df_adjusted_solar$wet_heat_loss -
    df_adjusted_solar$dry_heat_loss
```

Calculating Sweat Requirements

$$Sweat_{Max} = \frac{H_{Max}^{30^\circ C,\ Solar} * 3600}{2430}$$

$$IF\ H_{Dry}^{30^\circ C,\ Solar} < 0,\ Sweat_{Zero} = -\frac{H_{Dry}^{30^\circ C,\ Solar} * 3600}{2430} ELSE,\ Sweat_{Zero} = 0$$

```
# Create a new df with the sweat requirements

df_sweat_requirements <- data.frame(sweat_max <- df_evaporative_potential *
    3600/2430, sweat_zero <- -3600/2430 * df_adjusted_solar["dry_heat_loss"],
    wig <- df_adjusted_solar$wig, wind <- df_adjusted_solar$wind)

# Rename columns
colnames(df_sweat_requirements) <- c("sweat_max", "sweat_zero",
    "wig", "wind")


# Replace all values less than 0 with 0 per formula
df_sweat_requirements["sweat_zero"][df_sweat_requirements["sweat_zero"] <
    0] <- 0
```


A
B
Sweat (g / m²h)
Wind Speed (m / s)
0.0
0.5
1.0
1.5
2.0
2.5
100
200
300
400
500
600
0
50
150
wig
Nude
Straight
Moderately Curled
Tightly Curled