Estimating the Effect of Shade on Heat Stress in New Zealand Dairy Cows Using Two Published Models

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EXTENDED ABSTRACT

Objective: The objective of this study is to predict how much tree shade reduces heat stress in dairy cows using two published models which predict when heat stress will occur in dairy cows. The reduced solar radiation incident on a dairy cow in shaded conditions compared with the open should result in the models predicting a lower level of heat stress for that cow.

Method: The two models used to predict heat stress in this study are the ECCLIPS model (Turnpenny *et al.* 2000a, 2000b) and the Heat Load Index or HLI (Gaughan and Castaneda 2003). The ECCLIPS model developed by John Turnpenny and colleagues calculates the thermal balance for a dairy cow under specified climate and radiation conditions. The HLI calculates a single index value based on empirical weightings of input variables (air temperature, humidity, black globe temperature and wind speed) and predicts thermal stress will occur once a threshold value of the index (74) is exceeded.

Predicted heat stress in dairy cows was calculated using both models for a one week period in February 2005, at the Lincoln University Dairy Farm, Canterbury, New Zealand. Hourly mean climate and radiation data from 'daylight' hours (0800-1900 hrs, n=84) were input into ECCLIPS and HLI. The same data were then re-input, but with solar radiation levels reduced to 'Shade' conditions based on data from a study of tree-pasture interactions in the lower North Island (Douglas *et al.* 2006). The levels of cow thermal stress predicted by the heat stress models were compared for 'Open' and 'Shade' scenarios. If tree shade was effective in reducing cow heat stress, the models would predict a lower frequency of severe heat stress for the 'Shade' scenario compared with the 'Open' scenario.

Results: For both models, the predicted frequency of severe heat stress in the open was dramatically reduced under shade. ECCLIPS predicted that four hours severe heat stress in the open reduced under shade to zero hours of severe heat stress; and 44 hours of significant heat stress in the open reduced to 5 hours of significant heat stress in the shade.

HLI and ECCLIPS differed in the number of hours of predicted severe heat stress; for cows in the open, ECCLIPS only predicted four hours in the severe heat stress category, whereas HLI predicted 13 hours in the 'Hot' and 'Very Hot' categories (HLI>74).

Conclusions: Tree shade completely eliminated any occurrences of severe heat stress, whether predicted by ECCLIPS or the HLI. This result suggests that Friesian cows will benefit from shade even under relatively mild summer conditions in coastal Canterbury.

HLI and ECCLIPS differed in the number of hours of predicted severe heat stress. However, the thresholds for severe heat stress in these two models are set using different criteria. ECCLIPS predicts severe heat stress when the cow's evaporative cooling from sweat reaches its maximum possible value, and the cow must begin panting in order to maintain thermoneutrality. In contrast, the HLI threshold of 74 was set on the basis of various indicators of stress in dairy cows, e.g. reduced milk production, reduced feed intake or unusual levels of hormones in blood serum (Gaughan and Castaneda 2003).

Heat balance models or thermal stress indices like HLI can be used to investigate shade benefits elsewhere in New Zealand, provided a complete set of hourly climate data are available.

Comparison of ECCLIPS and HLI model predictions with field measurements of cow heat stress is needed to confirm reliability of these models under New Zealand conditions.

1. INTRODUCTION

The objective of this study is to predict how much tree shade reduces heat stress in dairy cows. This is done by using climate and radiation data for open and shaded conditions as inputs into two published models which predict when heat stress will occur in dairy cows. The reduced solar radiation incident on a dairy cow in shaded conditions compared with the open should result in a lower level of heat stress for that cow.

1.1. Background

Thermal stress in dairy cows occurs when the animal's thermo-regulatory mechanisms cannot maintain its core body temperature at a steady state. Because of their high heat production, lactating Friesian dairy cows are particularly susceptible to heat stress compared with other livestock (Berman 2005). Therefore shade is essential to minimise losses in milk production and reproductive efficiency (Collier *et al.* 2006). However most studies of shade effects on cows have been empirical studies typically carried out where summertime temperatures and humidity are high by New Zealand standards e.g. Queensland, Australia and the south-eastern United States (Gaughan *et al.* 1998; West *et al.* 2003). This makes it difficult to extrapolate the results of these studies to the milder New Zealand climate.

This problem can be solved by using thermal heat stress models which predict the level of cow heat stress based on the climatic conditions experienced by the cow, including the solar radiation flux intercepted by the cow's body. If New Zealand climate data are inputs into these models, then the level of thermal stress predicted by the models should be realistic for New Zealand dairy farms.
In this investigation, two heat stress models were used to predict:

1. Heat stress in dairy cows under New Zealand summertime conditions.
2. The extent to which shade from a single broadleaf tree might reduce heat stress in a cow, by reducing the solar radiation incident on the cow's body.

To do this, open field climate measurements from the Lincoln University Dairy Farm in Canterbury, New Zealand (43º 39' S, 172º 27' E, 18m ASL) were input to the heat stress models. The same data were then re-input, but with solar radiation levels reduced to 'Shade' conditions based on data from a study of tree-pasture interactions in the lower North Island (Douglas *et al.* 2006). The levels of cow thermal stress predicted by the heat stress models were compared for 'Open' and 'Shade' scenarios. If tree shade was effective in reducing cow heat stress, the models would predict a lower frequency of severe heat stress for the 'Shade' scenario compared with the 'Open' scenario.

1.2. The ECCLIPS and Heat Load Index models

The two models used to predict heat stress in this study are the ECCLIPS model (Turnpenny *et al.* 2000a) and the Heat Load Index (HLI; Gaughan and Castaneda 2003). The ECCLIPS model developed by John Turnpenny and colleagues calculates the thermal balance for a dairy cow under specified climate and radiation conditions. ECCLIPS was originally intended to predict the effects of long-term global warming on domestic animals (Turnpenny *et al.* 2000a and 2000b) but a modified version was later developed for modelling dairy cow thermal stress on an hourly basis over short time periods in Kenya (King *et al.* 2006). This study used the modified short-duration version of ECCLIPS. Within this modified model there are two sub-models.

1. The livestock feeding model uses inputs relating to cow metabolism to predict the metabolic heat produced by the cow. This sub-model is based on the AFRC model (AFRC 1993).
2. The metabolic heat produced in the livestock feeding model is then input to a heat balance model which predicts the size of the heat fluxes in and out of the cow's body.

The ECCLIPS model accounts for variations in cow metabolism and susceptibility to stress, as well as effects of the various climate and radiation factors. In contrast, the Heat Load Index or HLI (Gaughan and Castaneda 2003) calculates a single index value for heat stress based on empirical weightings of input climate variables (air temperature, humidity, black globe temperature and wind speed) and predicts thermal stress will occur once a threshold value of the index is exceeded.

Predicted heat stress in dairy cows was calculated for a one week period in February 2005, at the Lincoln University Dairy Farm. ECCLIPS and the HLI were used for both the 'Open' and 'Shade' scenarios described above.

2. METHOD

2.1. Data

Input data sets: Climate data from a summer study of cow temperatures at Lincoln University Dairy Farm (LUDF) were used. Data were measured for the week beginning 1 Feb 2005 at Broadfields, 3.3 km NE from the LUDF. Only data from 'daylight' hours (0800-1900 h) were used in the study.

Some climate data input into the models were hourly averages from the Broadfields data, but some data had to be transformed and/or estimated from other sources as there were no measurements available i.e.:

1. The climate data set did not include separate values for diffuse (R_d) and direct beam (R_b) solar radiation. These were calculated using relationships derived from solar radiation data gathered by Douglas *et al.* (2006) (see Section 3.2).
2. T_{sky} (the radiant temperature of the cow's environment) was calculated from T_{air} according to an approximation from Monteith and Unsworth (1990; pp 36-54).
3. For a well-irrigated dairy pasture, T_{ground} was assumed to equal T_{air}.
4. Cow albedo was calculated as 0.3 for a piebald Friesian cow using data from da Silva *et al*. (2003). Cow live weight was assumed to be 450 kg as there were no individual data available.
5. Wind speed measured at Broadfields was at a standard height of 10m above ground (Z = 10). Wind speed (U) at the approximate midpoint of a cow's body (U (Z = 1.2)) was calculated from Monteith and Unsworth (1990; pp112-115). Based on this, the wind speed at 1.2 m above ground will be 69% of the measured wind speed at 10 m.

Inputs for the metabolic heat (AFRC) model were based on typical values as there were no individual data for the LUDF cows relating to inputs such as feed ME or milk production.

Tree Shade Data: Tree shade reduces thermal stress in animals by partially intercepting direct beam solar radiation (R_b). To estimate tree shading under typical **New Zealand** conditions we used measurements of total and diffuse shortwave (400-1100 nm) solar radiation in the open and in the shade of a young poplar tree (*Populus nigra* x *maximowiczii*, approximately 10 years old) in the Pohangina Valley (Manawatu District, Lower North Island. 40º 10' S, 175º 45' E, 260 m ASL) (Douglas *et al*. 2006).

To measure solar radiation in the shade, an LI-200 pyranometer was located immediately to the south of the tree. Because the pyranometer was fixed in this position, it would be fully shaded only when the sun was at or close to its zenith. For this reason, R_d in the shade was calculated only from pyranometer readings at 1300 and 1400 h New Zealand Daylight Time.

In order to calculate a heat load index, a black globe temperature must be measured or estimated. Because no black globe temperature data were available from the Broadfields data, it was calculated using an empirical formula given in Hunter and Minyard (undated).

2.2 Analysis

ECCLIPS predictions: ECCLIPS predicts heat stress by calculating the heat lost from the animal's trunk through radiation and convection, and also by sweat (Et, W m^{-2}). Under increasingly warm conditions a cow will increase its Et up to a maximum determined either by a physiological limit to the cow's sweating rate (Emax, ~ 120 W m^{-2}) or a lesser figure determined by the relative humidity of the atmosphere i.e. under very humid conditions, the maximum rate of evaporation is limited by the atmospheric vapour pressure deficit rather than the cow's maximum sweating rate.

ECCLIPS predicts heat stress for cows in one of five categories based on the cow's Et:

SAFECOLD	Et = 17.0 W m^{-2} (minimum)
NO	Et = 17.0 W m^{-2} (minimum)
MILDHEAT	0.5 Emax > Et > 17.0 W m^{-2}
SIGHEAT	Et > 0.5 Emax and Et<Emax
SEVHEAT	Et > Emax

As the cow approaches Emax, it must lose additional heat by increasing evaporative heat loss from the respiratory tract, and so it begins to pant. ECCLIPS does not model this increase in respiration rate. Instead it classifies the cow as severely heat stressed (SEVHEAT) as soon as Emax is reached.

HLI calculation: In addition to running the ECCLIPS model, HLI was calculated for the LUDF data using the following formula (Gaughan and Castaneda 2003):

$$HLI = 34.1+0.26RH+1.33BGT-(0.82u)^{0.1} -\ln(0.4(0.0001+u^2)) \quad (1)$$

Where:
BGT is the black globe temperature in ^oC.
RH is the relative humidity of the air (%)
u is the air speed in m s^{-1}

For HLI, a threshold value of 74 is quoted for the onset of heat stress (Castaneda *et al.* 2004); therefore we expected that ECCLIPS would predict that cows were in the SEVHEAT category when HLI was equal to or greater than 74.

3. RESULTS

3.1. Climate Data

The data in Table 1 show that the weather over the study period was generally mild.

Table 1. Summary statistics for climate data during 'daylight' hours, Broadfields 1-7 February 2005. Data are in the form of hourly mean values (n = 84)

	T_{air} (^oC)	Wind speed m s^{-1}	R_b W m^{-2}	R_d W m^{-2}	RH (%)
Mean	21.1	3.39	225.9	199.6	79.6
s.d*	1.96	2.12	225.0	66.0	8.22
Min	16.5	1.22	5.5	25.1	50.2
Max	27.3	9.02	822.7	268.7	96.7

*s.d. is the standard deviation of the data.

Wind speed and solar radiation varied from day to day, but followed predicable diurnal patterns, i.e.:

1. Solar radiation peaked at 1300-1400 h (maximum solar elevation is ~1330 h New Zealand Daylight Time).
2. Wind speeds peaked during the afternoon period before dying away to a minimum before sunrise, a typical pattern for coastal Canterbury where an onshore NE wind is the prevailing wind (Ryan 1987).

3.2. Predicting diffuse and shade radiation from total solar radiation (Rt)

The data used for this analysis were from the Pohangina Valley study described in Section 2.1.

Predicting solar radiation in the shade of a tree: The solar radiation flux in the shade (R_{shade}) was calculated indirectly from $R_{shade} = R_t - R_{int}$, where R_{int} is solar radiation flux intercepted by the tree. R_{int} is highly correlated with the level of total solar radiation flux in the open (R_t). The relationship between R_{int} and R_t is non-linear, but when plotted as ln R_{int} vs. ln R_t yields a linear relationship (Figure 1).

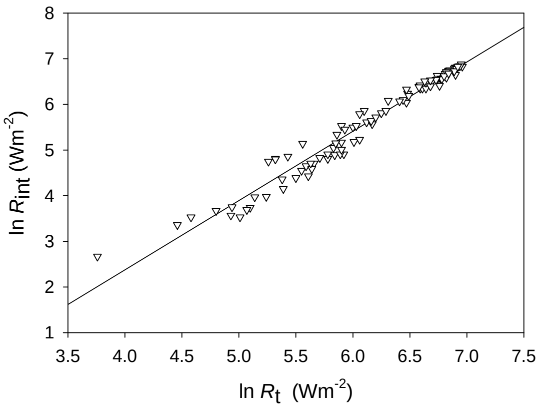

Figure 1. Ln R_t vs. ln R_{int} . The plotted regression line is $y = -3.7 + 1.52x$. $R^2 = 0.97$

The relationship in Figure 1 was used to predict average hourly R_{int} and R_{shade} for the LUDF over the period 1 -7 February 2005.

Diffuse versus direct radiation flux in the open: Average hourly R_d in the open was calculated as a fraction of R_t, and plotted against the fractional ratio of R_t/R_o, where R_o is the solar constant (the solar radiation flux incident on a surface perpendicular to the solar beam, approximately 1360 W m^{-2}) (Figure 2).

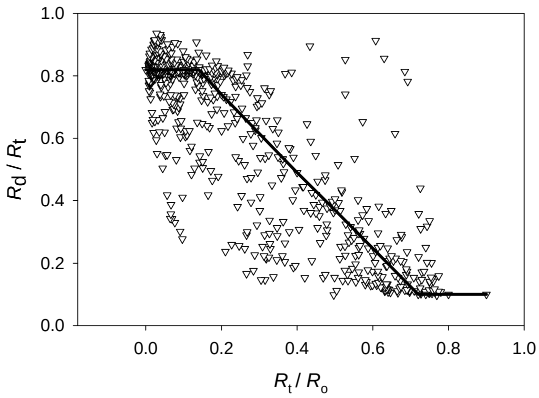

Figure 2. Open R_d/R_t versus R_t/R_o for January/February 1999, Pohangina Valley.

Also shown in Figure 2 is a three part regression relationship fitted to the data using the method described by Roderick (1999).This regression takes the form:

$Y = 0.82$, $X < 0.14$
$Y = 0.99 - 1.24X$, $0.73 \geq X \geq 0.14$
$Y = 0.10$, $X > 0.73$ (2)

Where Y is R_d/R_t
X is R_t/R_o

R_b (direct radiation) was then calculated as
$R_b = R_t - R_d$.

3.3. Predicted Thermal Stress in the Open and Under Shade

ECCLIPS predictions: ECCLIPS predicted that dairy cows in the open would experience severe heat stress for 4 out of 84 'daylight' hours (0800-1900 hrs) during 1-7 February 2005, and would experience significant heat stress during a further 44 'daylight' hours.

When ECCLIPS was re-run using predicted solar radiation levels under shade (but with all other model inputs unchanged) the incidence of severe and significant heat stress was drastically reduced, as shown by Table 2.

Table 2. Predicted frequency of heat stress classes in the open versus the equivalent stress class in the shade (n = 84).

Stress Class	Open	Shade
SEVERE HEAT	4	0
SIG HEAT	44	5
MILD HEAT	30	58
NO STRESS	4	18
SAFECOLD	2	3

In particular the reduction in frequency of severe and significant heat stress under shade was dramatic, with 1) four hours severe heat stress in the open reducing under shade to zero; and 2) 44 hours of significant heat stress in the open reducing to 5 hours of significant heat stress in the shade.

Heat load index predictions: Heat stress in the open and under shade was also predicted using the heat load index (HLI).

In the open, the HLI values seemed generally consistent with ECCLIPS predictions (Figure 3). When ECCLIPS predicted SEVERE heat stress, the HLI also predicted severe heat stress (HLI > 74). However, HLI also predicted severe heat stress on nine other occasions during the week when ECCLIPS only predicted SIGHEAT stress. On these occasions, air temperatures were quite high (>20^{o}C) but relative humidities or wind speeds were particularly low (50% to 60% and < 2 m s^{-1} respectively). It appears that ECCLIPS placed more weight on the low humidities than did the HLI, and predicted that the cows would not reach a maximum rate of evaporation from sweating.
In contrast, predicted HLI in shade never exceeded 70 on any occasion during 1 -7 February 2005, which is consistent with ECCLIPS predictions that no severe heat stress occurred in the shade. Mean HLI in shade was 60 compared with 67 in the open.

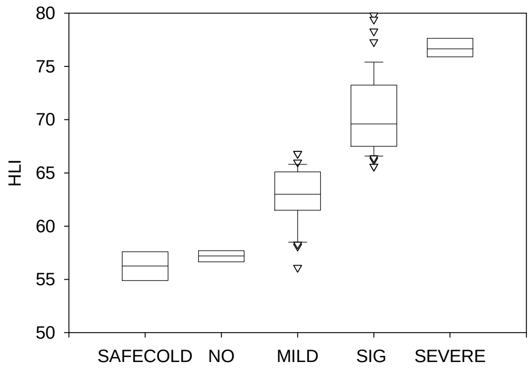

Figure 3. HLI vs. ECCLIPS Stress Codes, in the open (n = 84). Mid-line = median value, the boxes = the 25% –75% percentile range and the whiskers = 10%–90% percentile range of sample values.

4. DISCUSSION

4.1. Radiation Interception and Shade

Based on the data from Douglas *et al.* (2006), radiation interception by a typical poplar tree increases proportionally to the total solar radiation flux R_t. On a typical fine summer's day in New Zealand where R_t may exceed 1000 W m^{-2}, R_{shade} under a healthy poplar tree will be a less than 200 W m^{-2}. On cloudy days, tree shade will intercept less solar radiation due to a higher proportion of R_d in the total solar radiation flux. However, because total solar radiation levels are lower on cloudy days, R_{shade} is still unlikely to exceed 200 W m^{-2} most of the time.

Shade provided by other types of trees may vary with the density and orientation of foliage and branches in the tree crown, but poplar casts a relatively light shade compared with other common species used on New Zealand farms and so the shade levels used in this study are conservative.

4.2. Prediction of diffuse versus direct radiation

It is important to estimate the proportion of total solar radiation that is direct and diffuse when modelling thermal stress in animals. Firstly, because a diffuse radiation flux will be completely (or nearly so) intercepted by the body of a standing animal, whereas the proportion of direct radiation intercepted by the animal will never exceed ~25%, depending on the sun angle and how rotund the animals' body is (Monteith and Unsworth 1990;p59). Therefore the same amount of total solar radiation may result in different amounts of radiation intercepted by an animal, depending on the proportions of R_b and R_d.

The proportion of R_b and R_d also influences the effectiveness of shade. Under hazy summer conditions it may be possible to have a combination of high R_t with a high proportion of R_d. In these conditions shade will not reduce intercepted solar radiation by very much. Roderick (1999) reported the occurrence of these conditions in Queensland, Australia during the bushfire season when the atmosphere is particularly smoky. The hourly weather data from Pohangina Valley suggested that high R_d with a high R_t seldom occurs in New Zealand (Figure 2).

4.3. Predicting Heat Stress using ECCLIPS and HLI

Two heat stress models that include solar radiation flux as an input (HLI and ECCLIPS) differed in the number of hours of predicted severe heat stress; ECCLIPS only predicted four hours in the SEVERE HEAT category, whereas HLI predicted 13 hours in the 'Hot' and 'Very Hot' categories (HLI>74). However, the thresholds for severe heat stress in these two models are set using different criteria. ECCLIPS predicts severe heat stress when the cow's evaporative cooling from sweat reaches its maximum possible value, and the cow must begin panting in order to maintain thermoneutrality. In contrast, the HLI threshold of 74 was set on the basis of various indicators of stress in dairy cows, e.g. reduced milk production, reduced feed intake or unusual levels of hormones in blood serum (Gaughan and Castaneda 2003).

Because the thresholds are set differently for the two models, they may not be completely consistent in predicting severe heat stress in dairy cows. However, Figure 3 suggests that ECCLIPS and HLI respond in similar fashion to climate and radiation levels in the cow's environment.

4.4. Predicting the Effects of Shade on Heat Stress

Tree shade completely eliminated any occurrences of severe heat stress, whether predicted by ECCLIPS or the HLI. This occurred because peak solar radiation on sunny days was reduced from ~1000 W m^{-2} in the open to less than 200 W m^{-2} in tree shade.

Clear benefits of shade to dairy cows have been demonstrated in many overseas studies but these are typically under hotter conditions than encountered in New Zealand. However, this study suggests that Friesian dairy cows can become heat stressed in full sunlight when temperatures are in the mid-20 degree range and relative humidities are quite high (~70-80%). While cows are still capable of thermoregulation at these temperatures, this will require them to begin panting because sweating rates and cutaneous vasodilation will be at a maximum.

Note that this study assumed that no other climate variables other than solar radiation changed under tree shade. This is a reasonable assumption provided trees are well spaced apart. Where trees are planted as windbreaks or woodlots, the benefit from their shade will be offset by reduced wind speeds and higher relative humidities proximate to the trees which reduce the rate at which cows can lose heat by evaporation.

It is important to maintain air speed under shaded conditions. Even under warm conditions, Berman (2005) suggests that it is hard to heat-stress a housed Friesian cow when air speeds are > 2 m s^{-1}, presumably because of the combination of shade and adequate air movement over the cow. From that viewpoint, scattered individual trees are likely to be a much better choice for reducing heat stress in cattle under summer conditions in New Zealand.

5. CONCLUSION

Both ECCLIPS and the HLI predict that Friesian cows will benefit from shade even under relatively mild summer conditions in coastal Canterbury.

Risk of heat stress to Friesian cows in other New Zealand regions has been identified by Bluett *et al.* (2000) and Forrest (2005). Heat balance models or thermal stress indices like HLI could therefore be used to investigate shade benefits elsewhere in New Zealand, provided a complete set of hourly climate data are available.

Bluett *et al.* (2000) found that measurements of cow heat stress as indicated by physiology and behaviour under warm conditions in the Waikato region, New Zealand, were correlated with black globe temperature and temperature humidity index (a similar index to HLI). A similar comparison of ECCLIPS and HLI model predictions with measurements of cow heat stress is needed to confirm reliability of these models under New Zealand conditions.

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