CLIMATE CHANGE, CARRYING CAPACITY OF GRAZED PASTURES AND POTENTIAL BENEFITS OF WINDBREAKS, A SINGLE-SITE CASE STUDY.

by Roger Hosking WDA.

Synopsis

The purpose of this paper is to report on: climate change trends found in records of rainfall, temperatures, evaporation and wind at Braidwood; the adverse impact of climate change on livestock carrying capacity of grazed pastures and on rainfall runoff into farm water storages; the effect of wind run and wind direction on evaporation; and, the quantified potential benefits of windbreaks as a practical farm management strategy to counter the impacts of climate change.

The analyses involved the use of annual values derived from previously unpublished data in the original records of daily weather observations made at BoM station 069010 at Braidwood. The author has been the volunteer observer for this station since 1985. Annual carrying capacity of grazed pastures were derived from reliable tallies of livestock classes on a nearby well managed beef cattle operation.

The main results and conclusions are: that there have been significant trends in climate elements and in carrying capacity of pastures; that there is a close correlation between carrying capacity and the relative frequency of northerly winds; that wind run and wind direction are major factors driving potential evaporation; and, that windbreaks offer a practical method to reduce evaporation loss from farm dams and to extend the growing season of pastures.

Keywords and terms: beef cattle, Braidwood, carrying capacity, climate change, cloudiness, evaporation, farm dams, grazed pastures, livestock, rainfall, rainfall runoff, Soil Dryness Index, southern tablelands, temperature, wind direction, wind run, wind shelter, windbreaks.

Introduction

Braidwood (Lat. 35.45° S, Long. 149.80° E, elevation 652m, population 1100) is a small rural town 50 km from the coast on the gently undulating plateau of the southern tablelands of NSW, Australia. The value in using Braidwood as a case study to examine the local impact of global climate change lies in the extent and detail of the available observations and the remoteness of the site from major sources of air pollution. The relatively low population, small built-up area and lack of heavy industry produces a negligible ‘urban heat island’.

The town is surrounded by grazing land. Local industry focuses on grazed livestock, beef and fat lambs, and is dependent on the productivity of rain-fed pastures. Drinking water for stock in farm dams and natural watercourses is dependent on runoff and affected by evaporation.

Empirical observations and anecdotal evidence from long-term landholders suggest a prolonged and substantial deterioration in pastoral conditions at Braidwood. A long history of detailed weather observations and of livestock numbers on a district grazing property were examined for evidence of climate change.

Significant trends were found in a wide range of climate elements over various time spans including a rapid increase in maximum temperature, a decrease in rainfall and a marked decrease in runoff. Grazed livestock numbers have declined by 35% in the last twenty years.

Changes in the wind pattern are a key factor in the changes that are occurring in the local climate. Nearly all of the trends and relationships found in the Braidwood records can be traced back to aspects of wind. This suggests that the climate change culprit is not simply ‘global warming’ but a more fundamental alteration of continental scale air pressure systems.

Unlike rainfall and temperature, wind speed (and thus wind run) is a factor that can be modified by on-farm management. Windbreaks present an opportunity to arrest the decline in carrying capacity. One aspect of windbreaks is the possibility of ongoing earning of tradable carbon credits while at the same time improving the microclimate for pasture growth. The concept of ‘alley farming’ with multiple rows of windbreaks deserves serious consideration.

Even sparse windbreaks can reduce average wind speeds by 30% for a considerable downwind distance. The calculated potential benefits of windbreaks at Braidwood resulting from a 30% reduction in wind speed include a 23% reduction in evaporation and a 30% boost in the number of days with a Soil Dryness Index below 50 mm, i.e., soil moisture conditions suitable for pasture growth. The ideal orientation of windbreaks to provide shelter from the most damaging wind directions in terms of high atmospheric evaporative demand also offers shelter from cold stress for livestock.

Data sources and Treatment

The weather records used are those for Met. Bureau Stn. No. 069010, formerly at the Post Office and since 1986 at this author's residence at 21 Wallace St. Braidwood, the two sites are 750 m apart. The Post Office records are for rainfall, temperature and wind direction. A wider range of climate elements have been recorded since 1986. Private and reliable stock counts for a well managed beef cattle operation in the Braidwood district were provided confidentially.

Carrying Capacity. Annual carrying capacity of grazed pastures were derived from biannual age and gender tallies of beef cattle, converted to Dry Sheep Equivalents (DSE) per hectare using values given in "Dry Sheep Equivalents for comparing different classes of livestock". (McLaren 1997).
The stock counts are reliable but details are deliberately not provided to preserve requested anonymity. In effect, annual carrying capacity serves as a proxy for pasture productivity.

Rainfall. Monthly totals for the years 1888 to 1919 were supplied by the Bureau of Meteorology. Daily rainfalls for the years 1920 to 2005 are from the original observer sheets and journals.

Temperature. Screened maximum and minimum air temperatures are from the original observer journals for 50 years, 1945-1974 and 1986-2005 at two sites 750 m apart. The two data sets are considered to be compatible for maxima but not for minima due to differences in nocturnal cold air drainage in winter. Dewpoint temperature derived from screened morning wet-bulb and dry-bulb temperatures for the years 1986-2005 were time-corrected to 9 am AEST.

Evaporation. Strictly speaking 'potential' evaporation, was measured with an Australian class 'A' standard evaporimeter open to the atmosphere and fitted with a bird guard, 20 years 1986-2005.

Cloudiness. A visual estimate of the amount of the sky dome obscured by cloud at the time of the morning weather observation, 20 years 1986-2005. Visual estimates are prone to error but all these are by the one observer so any error should be consistent. On days when the sky was obscured by radiation fog at the time of observation it is treated as 50% cloud since fog normally clears by mid morning.

Wind Direction. Morning wind direction, to the nearest of eight compass points, tends to reflect the general circulation of air and avoid afternoon and evening sea breezes. Observations were recorded at the Post Office during the years 1947-1960 and 750 m away at 21 Wallace Street since 1985. The original wind vane still exists and simultaneous direction indications are similar.

Wind Run. Strictly speaking 'run-of-the-wind', the distance travelled by air moving past a fixed point, is measured with a spinning-cup anemometer at two metres above ground level, 19 years 1987-2005. Average wind speed (km/hr) is wind run (km) divided by the number of hours in the period measured.

Soil Dryness Index. (SDI) (Mount 1972). The index accommodates seasonal variation in wind run and evaporation and is calculated from daily maximum temperature and rainfall. A grassland version of the index was developed by this author (Hosking 1990) from daily water levels in a creek draining a 3,800 ha grazed pasture catchment. In regular use for twenty years, the index has been accurate to within plus or minus one millimetre per month between runoff events.

Runoff rainfall. Modelled using Mount's Soil Dryness Index (SDI). Provides an estimation of runoff as rainfall equivalent (mm). Runoff is the sum of two components of the index: flash runoff (FRO) from intense rainfall; and soil capacity overflow (SCO) when rainfall reduces the daily SDI to zero indicating soil saturation.

Statistical Significance. Monthly and annual values were derived from these data and used to examine climate change trends and to find correlations between various elements. Correlation coefficients were used to fnd statistical significance, after Linacre (1992, 329). The statistical significance of all of the material presented here is at the 5% level or better. Most of the findings are significant at or below the 1% level. Significance at the 1% level means that the likelihood that a found trend or relationship was due to chance is less than one in a hundred.

Other work on Wind Shelter

I am indebted to the overview of research into the effects and potential benefits of windbreaks in southern and south-eastern Australia in “Trees for shelter - A guide to using windbreaks on Australian farms” (Cleugh 2003).

Numerous findings reported by Cleugh that are considered likely to be relevant to the potential benefits of windbreak shelter in this district are summarised:

Reduction of atmospheric evaporative demand contributing to:
- reduced plant stress (pp 5, 7, 28).
- conserved soil moisture, delayed soil water depletion (pp 5, 7, 29).
- improved water use efficiency, net gain in dry years (pp 7, 28, 29, 30, 34).
- increased leaf area, growth rate and plant biomass (pp 28, 30, 32, 45, 49).
- improved agricultural productivity where wind is a limiting factor (p 34).
- reduced water losses from farm dams (pp 32, 54).

Amelioration of low winter temperatures contributing to:
- enhanced winter pasture growth in upland SE Aust. (p 7).
- improved efficiency in animal production (p 4)
- reduced wind chill, protection of vulnerable livestock in upland SE Aust. (pp 7, 32).

A model was developed to integrate data shown by Cleugh (pp 14, 15, 17 & 21). The close linear fit between the model and Cleugh (N=42, R = 0.991) indicates that a very high degree of confidence can be placed in the calculated values shown in Table 1 (on page 15 below).

Available 'long-term' records.

The Post Office weather records are for rainfall (since 1888, daily since 1920), maximum and minimum air temperatures (daily, 1945-1974) and wind direction (daily, 1947-1960). These plus additional weather elements have been recorded since 1986. The longer term data provide a basis for comparison with some of the changes that have occurred since 1986.

Conventionally, climate change is described in terms of linear (straight line) trends and the rate of change is expressed as units per decade. This convention is adhered to and the levels of significance of found trends are also given. The main changes evident in the local Braidwood climate, decreasing rainfall and increasing maximum temperature, conform with the wider continental scale changes found by the CSIRO, Met. Bureau and others. These changes are real and unlikely to be temporary.

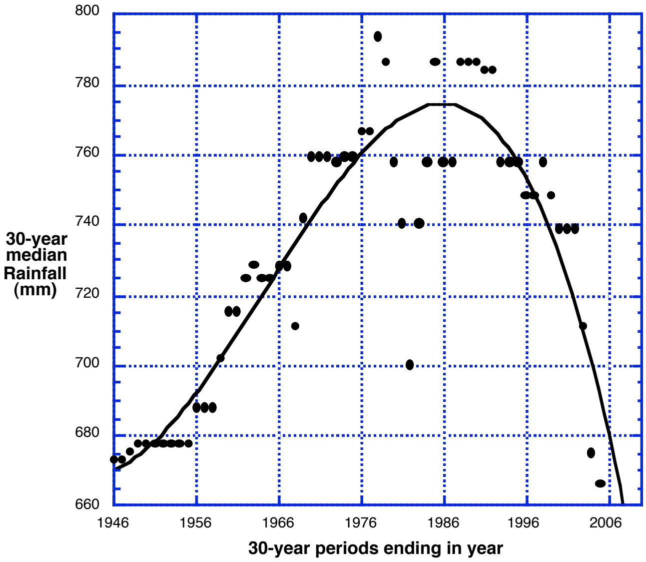
Annual total Rainfall

From the 118-year history of rainfall at Braidwood, the long-term average annual total rainfall is 720 mm and the median is 676 mm. The long-term trend is an increase in annual rainfall at the rate of 6 mm per decade but this trend is not significant.

Rainfall is highly variable. Conventionally, thirty years of rainfall records are considered adequate to describe a climate (Linacre 1992, 119). The median is the middle value and a measure of 'normal' in a set of records. For any 30-year period, 15 years are above and 15 years are below the median for that period. The progressive 30-year medians shown in **Figure 1** smooth the normal annual variability and illustrate the distinct decline in rainfall at Braidwood in recent years. The curve in the Figure accounts for 82% of the variation. The span of years shown has been selected to match the spans of available temperature and wind direction records.

Each of the last five consecutive years (2001 to 2005) has been below the long-term median and barring record high rainfall in December, 2006 will be the sixth such year. This run of years is not unprecedented but it is the longest run below the long-term median in the 96 years since 1910. Ten-year total rainfall for 1996-2005 is the lowest since 1904-1913.

Figure 1.
Successive 30-year medians of annual total RAINFALL for sixty periods 1917-1946 to 1976-2005 at Braidwood.



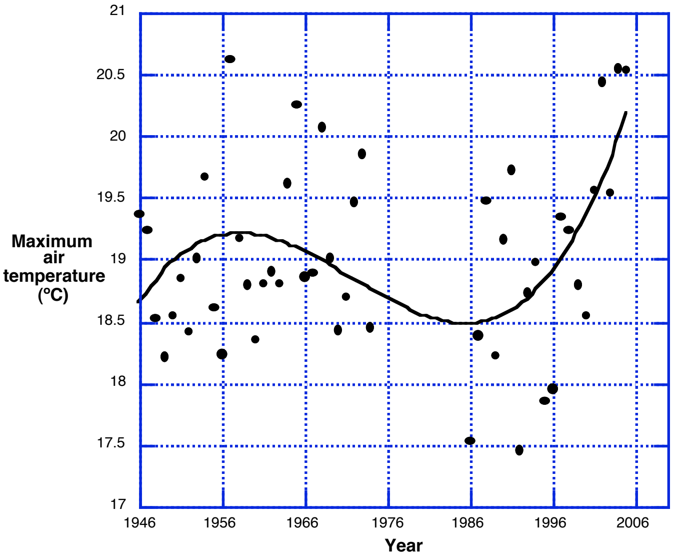
Annual average daily Maximum Temperature

Fifty years of temperature records span a period of 61 years, observed at the Post Office for the years 1945-1974, an eleven year gap, then at 21 Wallace St. for 1986-2005. The two sites are 750 m apart but the data sets of screened maximum temperature are considered to be compatible. The long-term average daily maximum temperature is 19.02 °C. The long-term trend in the combined data set is an increase at the rate of 0.05 °C per decade, but this trend is not significant.

The curve fit in **Figure 2.** illustrates the marked increase in annual average daily maximum temperature in recent years. Conventionally, fifteen years of air temperature records is regarded as an acceptable time span to describe a climate (Jagannathan et al. 1967, 13, quoted in Linacre 1992, 120). The trend for the 15 years 1991-2005 was an increase at the rate of +1.43 °C per decade, significant at the 1% level. The rate of increase in maximum temperature may be accelerating. The rate for the ten years 1996-2005 was +2.38 °C per decade and this trend is also significant at the 1% level. It is speculated that part of the increase is due to a decline in 'global dimming' - reflection of solar radiation by particle pollution in the atmosphere which in the past has suppressed 'global warming'.

Figure 2.

Annual mean daily MAXIMUM TEMPERATURE (°C) at two sites 750 m apart at Braidwood, 1946-1974 and 1986-2005.



Three of the four highest annual average daily maximum temperatures in fifty years of records have occurred since 2001. Average daily maximum temperature in 2006 is the hottest on record and conforms with the trend shown in Figure 2.

Relative frequency of morning Wind Direction

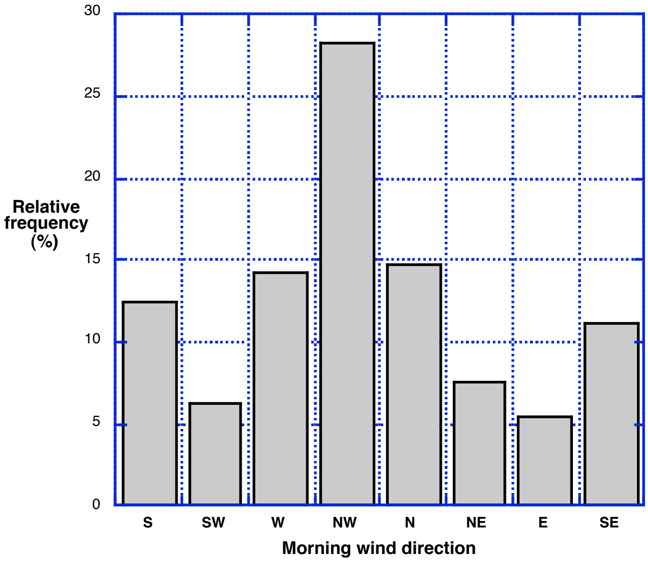
There are 34 years of records of morning wind direction which span 59 years, 1947-1960 (at the Post Office) and 1986-2005. The relative frequency of wind directions, expressed as the percentage of all observations, are shown in **Figure 3.** These provide a base for comparison with the changes that have occurred. North-west is the dominant direction in both data sets with little change in relative frequency, 27% at the Post Office and 29% since 1986.

The two sites are 750 m apart. Though the two wind vanes continue to indicate similar directions, the relative frequency of diametrically opposed directions were compared to minimise the effect of site change and local shielding. The two opposing wind directions with the greatest change in relative frequency are South-westerly and North-easterly. The trends over the 59 years spanned by these records are shown in **Figure 4.** The trends in both of the directions shown are significant at the 0.1% level.

The progression of day-to-day changes in local wind direction is normally anticlockwise. As a generalisation for Braidwood, wind from the North and North-west introduces drier air from the inland resulting in warmer temperatures, less cloud, and less chance of rain. The opposite can be said for South and South-easterly winds bringing cooler humid air from the coast.

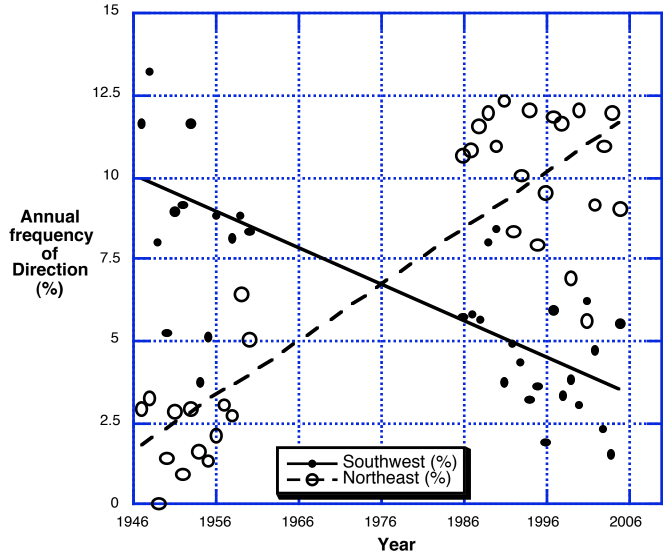
Figure 3.

Relative frequency (%) of morning WIND DIRECTIONS at Braidwood, 34 years 1947-1960 and 1986-2005.



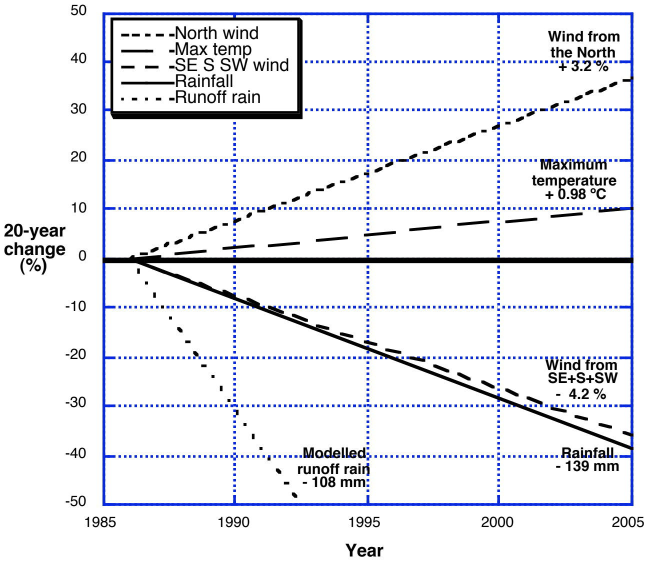
At this latitude, wind direction is the result of air pressure systems moving from west to east across the continent. Cold fronts associated with lower pressure cells in the Southern Ocean are relatively frequent, more so in winter. The trends in Figure 4 offer evidence that continental climate change involving large-scale variation of air pressure systems is occurring.

Figure 4.
Long-term trends in annual frequency of two diametrically opposed morning WIND DIRECTIONS Southwest (solid line) and Northeast (broken line) at Braidwood, 1947-1960 and 1986-2005.



Twenty-year Trends in Climate elements.

Figure 5.
A quick schematic summary of some CLIMATE CHANGES evident at Braidwood. Trends in annual data over 20 years 1986-2005 expressed as a percentage of the average of all records for the weather element, the tag labels show the change per decade for the element.



Daily observations since 1986 permitted examination of numerous climate elements in relation to possible climate change during the twenty year period to the end of 2005. A 'quick and dirty' overview of some of the substantial changes that have occurred over the last twenty years is shown in **Figure 5**.

Rainfall. Annual total rainfall has decreased at the rate of -139 mm per decade, significant at the 5% level. The decrease per decade in rainfall is equivalent to 20.6% of the long-term median. Annual rainfall is significantly correlated with South-easterly wind, cloud cover, and of course with runoff rainfall.

There appears to be a distinct seasonal variation involved which accounts for nearly all the change in annual rainfall. Total rainfall for the six months March to August each year has decreased at the rate of 133 mm per decade, significant at the 2% level.

Runoff rainfall. Modelled annual runoff has decreased at the rate of -108 mm per decade, significant at the 1% level. Average annual runoff for the twenty years 1986-2005 is 131 mm.

Maximum temperature. Annual average daily maximum temperature has increased at the rate of +0.98 °C per decade, significant at the 1% level. Maximum temperature is positively correlated with evaporation and negatively correlated with cloud cover and Southerly wind direction.

Minimum air temperatures. No significant trend is evident in the data, nor for incidence of frosts.

'Average' air temperatures where 'average' is the sum of maximum plus minimum divided by two. The annual 'average' daily temperature has increased at the rate of 0.59 °C per decade, the rise is significant at the 1% level. This measure is often used by commentators on 'global warming' (heating).

Air temperature range. The annual average daily difference between maximum and minimum temperatures has increased at a rate of +0.78 °C per decade, significant at the 5% level. This trend is being driven by changes in maximum temperatures and is likely to be imposing additional physiological stress on pasture plants and possibly on livestock.

Dewpoint temperature. This provides a guide to atmospheric water content. Standardised to 9 am Australian Eastern Standard time, dewpoint has risen at the rate of +0.57 °C per decade, significant at the 1% level. The rise is less than that of maximum temperature and as a result atmospheric moisture has declined.

Cloudiness. Morning cloud cover has declined at the rate of -3.6% per decade, significant at the 5% level. This conforms with dewpoint rising more slowly than maximum temperature. Cloudiness is correlated with rainfall, temperatures, evaporation and wind direction.

Water temperature range. Temperatures 5 mm below the surface of water in the evaporation pan are measured with a floating maximum-minimum thermometer. The range in water temperatures has increased at the rate of +1.28 °C per decade, significant at the 0.1% level. The increase is at a faster rate than that of maximum air temperature and has a positive impact on evaporation rate.

Evaporation. There is no significant trend in annual total potential evaporation over the twenty-year period, however, both wind run and evaporation data conform to fitted curves. The rate of change per decade in evaporation for the ten years 1996-2005 is +258 mm, significant at the 1% level. Evaporation is significantly correlated with maximum temperature, cloud cover, wind run and South-easterly wind.

Wind run. There is no significant trend in annual total run-of-the-wind over the twenty-year period. The best fit is a curve and it is speculated that the trend is associated with a shift in wind direction from the southerly quarter to the northerly quarter and continental changes in air pressure systems.

Wind directions. The relative frequency of some morning wind directions have changed more than others. The southern quarter (SE + South + SW) has decreased at the rate of 4.8% per decade, significant at the 5% level. The decrease in South winds is significant at the 1% level; Southerly winds are significantly correlated with cloudiness, rainfall, runoff rain, maximum temperature and Soil Dryness Index. Both Southerly and Northerly winds are correlated with carrying capacity of pastures.

Impacts of Climate Change

Carrying Capacity of Grazed Pastures

Confidential twice-yearly stock counts from a well-managed beef cattle operation near Braidwood were made available to the author on condition of anonymity. The counts indicate a good deal of variation in response to seasonal conditions. Tallies for various age classes were converted to Dry Sheep Equivalent (DSE) using tables provided by NSW Agriculture, and annualised values for DSE per hectare were derived. These figures serve as a proxy measure of the productivity of grazed pastures in the district see **Figure 6**.

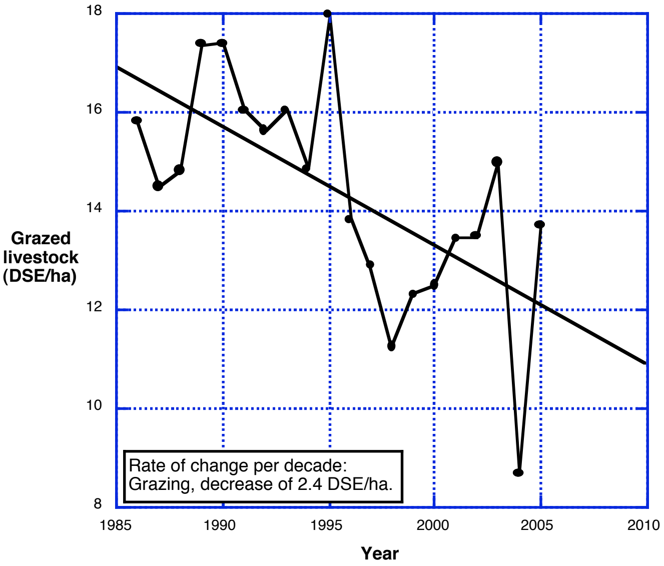
The average carrying capacity was 13.8 DSE/ha. For the 20 years 1986-2005 the linear trend has been a decrease at the rate of -2.4 DSE/ha per decade, significant at the 1% level.

To put this another way, the decrease in carrying capacity in the last 20 years is 34.8% of the average and the likelihood that this result was arrived at by chance is less than one in a hundred.

Surplus pasture on the property in good seasons is conserved and fed out in leaner times which has a buffering effect on livestock numbers. Annual stocking rates do not correlate well with annual total rainfall although both are declining. There are significant inverse relationships between annual carrying capacity and maximum temperatures, Northerly winds and year-to-year changes in wind run. The decline in annual carrying capacity is linked to climate change

Figure 6.

Annualised CARRYING CAPACITY of pastures at Braidwood, 20 years 1986-2005. Numbers and age-classes of beef cattle expressed as Dry Sheep Equivalents (DSE) per hectare.



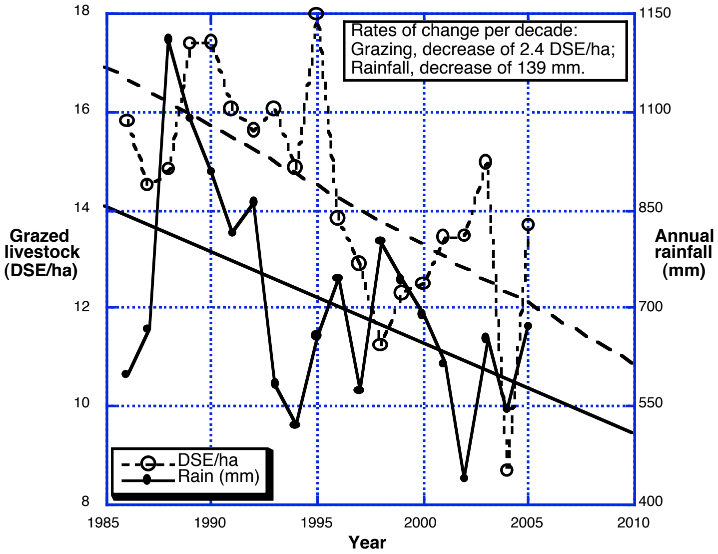
Rainfall and Carrying Capacity

For the 20 years 1986-2005 the trend in annual rainfall has been a decrease at the rate of -139 mm per decade. A comparison of the trends in rainfall and carrying capacity is shown in **Figure 7.**

The trends in both rainfall and carrying capacity are declining but the correlation between annual values for these two variables is not significant. In this case, annual total rainfall is not a reliable direct indication of grazed livestock numbers. Colder temperatures suppress pasture growth and limit the benefit of winter rainfall. The correlation between annual carrying capacity and nine-month total rainfall for September to May is significant at the 5% level. Runoff rainfall and to some extent winter

Figure 7.

Annual CARRYING CAPACITY of grazed pastures (beef as DSE/ha, broken lines) and annual total RAINFALL (mm, solid lines) at Braidwood, 20 years 1986-2005.



rainfall are of little direct benefit to pastures. Annual totals also mask the effect of timing of rainfall during a growing season which can be a crucial factor.

Maximum Temperature and Carrying Capacity

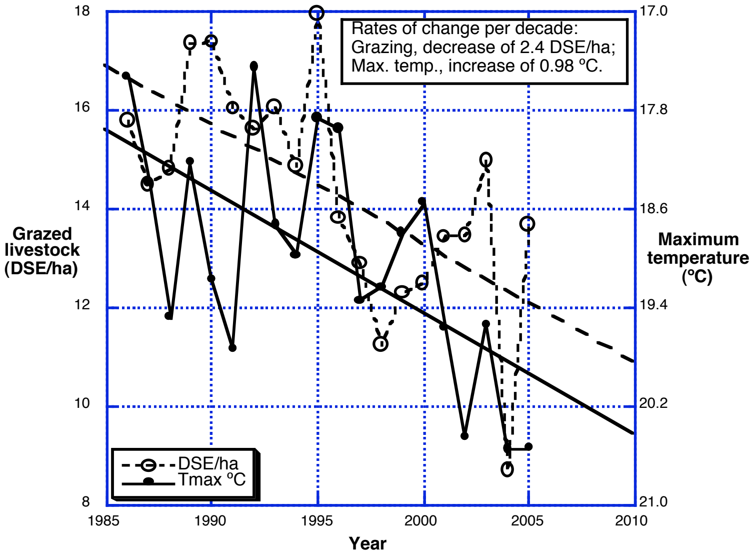
There is an inverse relationship between annual average daily maximum air temperature and annual carrying capacity of pastures. The parallel trends in **Figure 8.** are striking. It should be noted that the temperature scale on the right hand side has been inverted to assist comparison.

For the 20 years 1986-2005 the trend has been an increase in daily maximum temperature at the rate of 0.98 °C per decade. The correlation between annual average maximum temperature and annual carrying capacity is significant at the 5% level.

The reason for the link between maximum temperature and carrying capacity is unlikely to be due to temperature alone. 'Global warming' may well be the primary cause but rising maximum temperature is associated with numerous other factors including changes in the wind pattern.

Figure 8.

Annual CARRYING CAPACITY of grazed pasture (DSE/ha, broken lines) and annual mean daily MAXIMUM TEMPERATURE (°C, solid lines) at Braidwood, 20 years 1986-2005.
Note: the temperature scale is inverted to simplify comparison.



Northerly Winds and Carrying Capacity

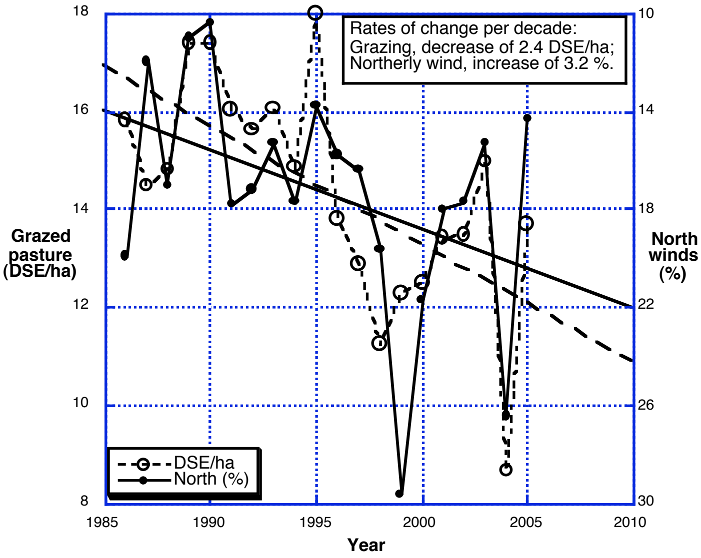
The twenty-year trend in the relative frequency of Northerly morning wind direction is increasing but is barely significant at the 10% level. However, a close and inverse relationship between the relative frequency of Northerly winds and the carrying capacity of grazed pastures is shown in **Figure 9.** The wind frequency scale is inverted. The correlation between Northerly wind and carrying capacity is significant at the 0.1% level.

There is a similarly strong correlation between the relative frequency of Southerly winds, which is decreasing, and carrying capacity, again significant at the 0.1% level. Southerly winds are significantly correlated with cloudiness, rainfall, runoff rain, and inversely with maximum temperature and Soil Dryness Index.

The change in wind pattern is having a significant and detrimental effect on pasture productivity.

Figure 9.

Annual CARRYING CAPACITY of pastures (beef as DSE/ha, broken lines) and annual relative frequency of morning WIND from the NORTH (%, solid lines) at Braidwood, 20 years 1986-2005.
Note: the wind frequency scale is inverted to assist comparison.



Modelled Runoff rainfall

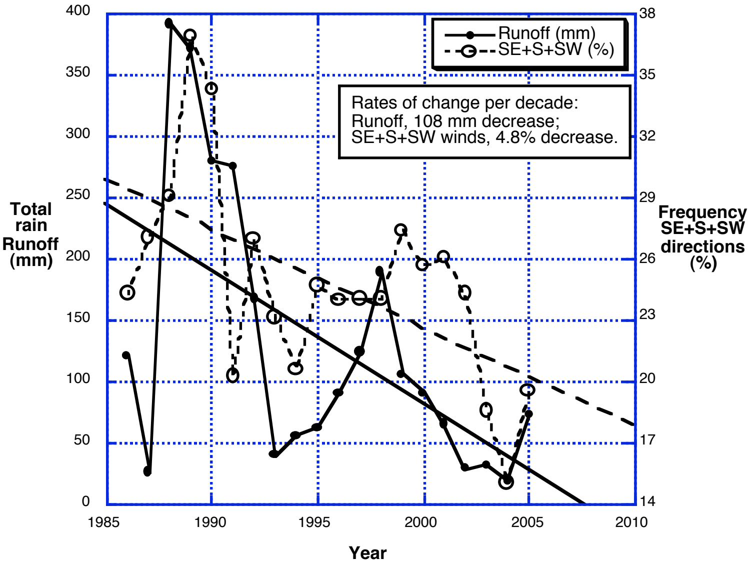
Annual runoff is closely associated with the relative frequency of wind from the Southeast, South and Southwest as shown in Figure 10. The correlation between runoff and the total frequency of wind from these three directions is significant at the 1% level.

Runoff rainfall is modelled using a grassland version of Mount's Soil Dryness Index. Surplus rainfall over and above the capacity of the root-zone soil to hold water is runoff both horizontal on the surface into creeks and rivers and vertical into the subsoil. In this district the latter eventually emerges at the surface via springs. Runoff is the source of water for livestock.

Average runoff for 1986-2005 was 131 mm of rainfall equivalent. The twenty-year trend in annual runoff is a decrease at the of -108 mm per decade, significant at the 1% level. The total relative frequencies of morning wind from the SE+S+SW has decreased at the rate of -4.8% per decade, also significant at the 1% level.

Figure 10.

Trends in annual total rain RUNOFF modelled by Soil Dryness Index (mm, solid lines) and annual total frequency of morning WIND DIRECTIONS SE + S + SW (%, broken lines) at Braidwood, 20 years 1986-2005.



Perhaps more tellingly, the <u>proportion</u> of annual rainfall that runs off has also fallen; the change is at the rate of -10.3% per decade, significant at the 1% level. The decline in runoff is faster than the decline in rainfall. This trend has an economic impact on the adequacy of storage capacity and on the durability of farm dams providing water for livestock, and on creek and river flows.

Aspects of Wind

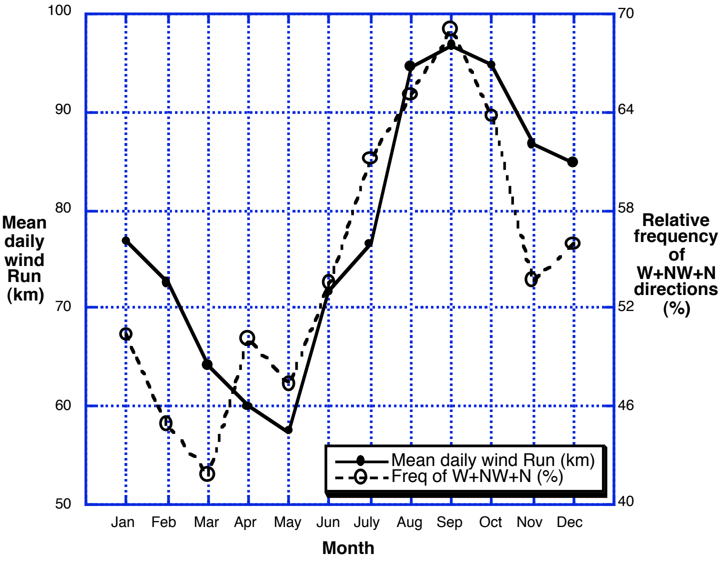
Seasonal variations in Wind

Data for the years 1986-2005 show a marked seasonality in average monthly run-of-the-wind (wind run) and in relative frequencies of West+NW+North wind directions at Braidwood, see **Figure 11.** The correlation between these two variables is significant at the 1% level.

The three months with the lowest wind run are in autumn, March to May, while the three highest months are in late winter / spring, August to October. The three most frequent morning wind directions are West (11%), North-west (29%), and North (18%). The total relative frequency of these three directions also varies during the year and closely matches the seasonal variation in wind run, August to October are the also the three months with the highest frequencies of West+NW+North.

Figure 11.

Monthly average daily WIND RUN (km, solid line) and relative frequency of morning WIND DIRECTIONS W plus NW plus N (%, broken line), from daily observations at Braidwood.
Data: Run 19 yrs 1987-2005 and Directions 20 yrs 1986-2005.



Wind and Climate

Trends in the relative frequencies of wind direction and totals of wind run indicate that a subtle variation in air pressure systems is occurring and support the contention that the underlying cause of climate change at Braidwood is change in the wind pattern. It is speculated that these trends in wind are associated with climate change on a continental scale as found by Bureau of Meteorology, CSIRO and others.

The annual data demonstrate strong interrelation between aspects of wind, other climate elements, and carrying capacity of grazed pastures, see **Figure 12.**

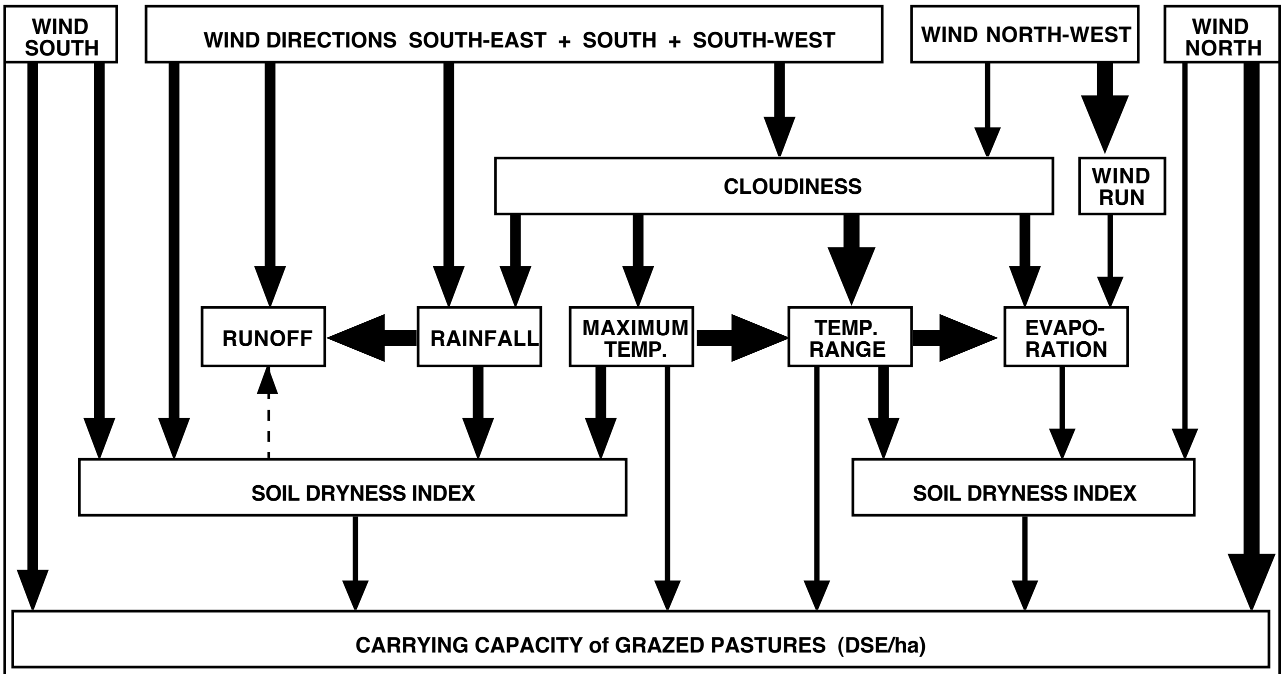
All of the correlations shown are significant at the 5% level or better. The arrows show the logical sequential order of events from cause to effect. On a day-to-day basis, wind is a root cause of weather and not the result of it. For example: South-easterly wind introduces cool, moist air leading to more cloud and rain; North-westerly wind introduces warm, dry air leading to higher maximum temperatures and greater evaporation; and not vice versa.

Soil Dryness Index does not constitute a climate element, nor does it intercept the effects of climate elements on carrying capacity. The index is influenced by the various climate elements and successfully models the daily deficit in soil moisture under grazed pastures. The link between runoff and Soil Dryness Index is a feedback loop. Runoff occurs when rain saturates the soil at which point the index is zero or, if necessary, the index is manually reset to zero.

Wind Run and Evaporation

Evaporation has negative impacts on soil moisture, plant growth, the carrying capacity of pastures, runoff rainfall and on water supplies held in farm dams. Annual totals of evaporation and wind run for the

Figure 12.
Significant correlations from cause to effect between of wind, climate elements and carrying capacity of pastures at Braidwood (from daily observations, 20 years 1986-2005).



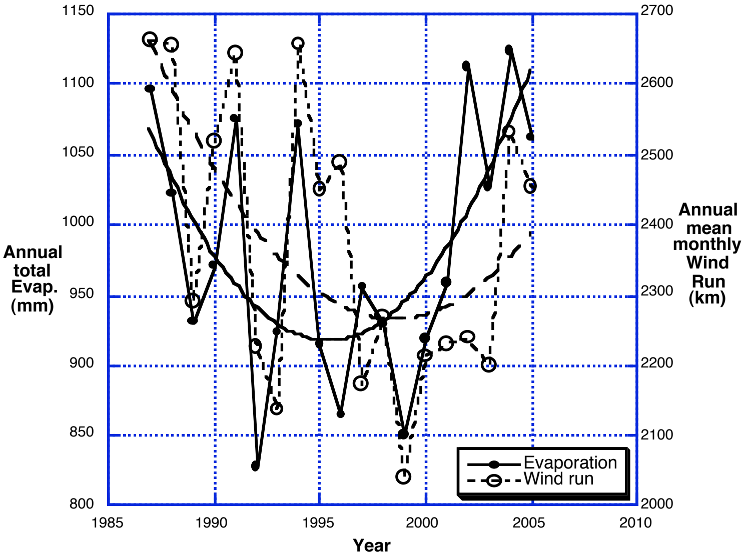
The arrows indicate the direction from cause to effect. The thickness of the linkage line indicates the strength of the correlation. For example, the diagram shows three significant relationships with Evaporation; Wind run is significant at the 5% level, Cloudiness at the 1% level, and Diurnal temperature range at the 0.1 % level.

nineteen years 1987-2005 are shown in **Figure 13.** The correlation between annual wind run and annual total evaporation is significant at the 5% level.

Over the span of years, both annual evaporation and annual wind run conform better to curves than to simple linear trends. For the ten years 1996-2005 the rate of increase in evaporation is +258 mm per decade, significant at the 1% level. The increase of 258 mm in the last ten years is equivalent to 26% of the twenty-year average annual evaporation.

Evaporation is sensitive to both wind run and to maximum air temperature. The correlation between annual average maximum temperature and annual total evaporation is significant at the 2% level. A model was developed to separate the effects of maximum temperature and wind run on monthly total evaporation. The model accounts for 92% of the variation in evaporation in 228 months in the years 1987-2005.

Figure 13.
Annual total EVAPORATION (mm, solid lines) and annual average monthly WIND RUN (km, broken lines) at Braidwood, 1987-2005. The fitted curves may indicate continental-scale wind changes.



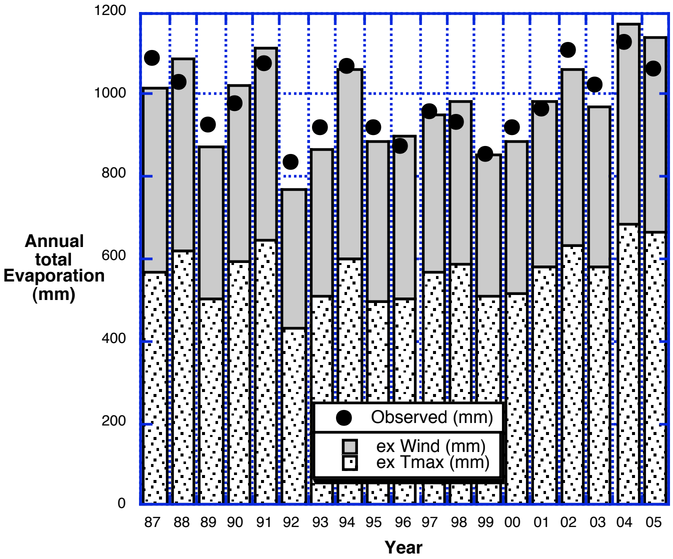
Model equation: Monthly total evaporation (mm) = -45.246-0.04207*x+0.00198*x^2

where “x” = 7.41 * monthly mean daily maximum air temperature plus 2.47 * square root of monthly total wind run

It is estimated that on average, 56% of annual total evaporation at Braidwood is due to maximum temperature and 44% is due to wind run. The contribution to evaporation by each of the two components, wind run and maximum temperature, is shown in **Figure 14.**

Figure 14.

Annual total EVAPORATION (mm) at Braidwood. Observed total and summed contributions by WIND RUN and MAXIMUM (air) TEMPERATURE from a model which accounts for 92% of the variation in monthly total evaporation, 228 months 1987-2005.



Wind Direction and Evaporation

As discussed above, annual wind run is related to annual wind direction frequency and monthly wind run is related to monthly evaporation. The daily weather records for 1987-2005 permitted the interplay between wind direction, wind run and evaporation to be examined in greater detail.

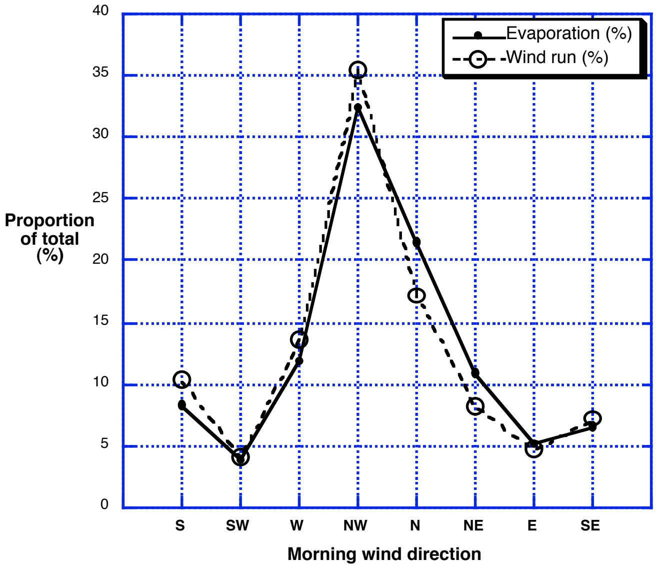
There is a close association between morning wind direction and wind run during the following 24 hours. The matching proportions of total evaporation and total wind run following morning wind direction are shown in **Figure 15.** The correlation between daily wind run and daily evaporation for the eight wind directions is significant at the 0.1% level.

The dominant wind direction is North-west. The relative frequency of this direction has changed little over the years, it was 27% for 1947-1960 at the Post Office, 29% for 1986-2005. North-west was the most frequent wind direction in 28 of 34 years. The frequency of Northerly wind is increasing while the frequency of Southerly wind is decreasing.

Clearly, North-westerly winds are the most frequent, are associated with the highest wind runs, have by far the greatest impact on evaporation, and is potentially the most damaging wind direction for pastures and water storages.

Figure 15.

Proportions (%) of total EVAPORATION (solid line) and total WIND RUN (broken line), in the 24-hour periods following morning WIND DIRECTIONS at Braidwood, 19 years 1987-2005.



Potential Benefits of Windbreaks

Climate change is a global problem that is probably the result of activities by the global society, including excessive breeding. Individual landholders are faced with the problem of devising management strategies to cope with and counteract the effects of climate change. Any successful strategy will need to offer some prospect of paying off in the relatively short term if it is to gain widespread acceptance.

Previous sections above have discussed the climate elements being affected by climate change and the resultant decline in carrying capacity of pastures. This section builds on the previous findings to investigate whether windbreaks are merely a ‘feel good aesthetic palliative promoted by environmentalists’ or whether they offer real and measurable advantages at the paddock level.

Wind, and particularly wind direction, is shown to be a key component of the local climate. Figure 12 (on page 12) summarises the network of relationships between climate elements. With one exception, none of the climate elements influencing carrying capacity shown in Figure 12 can be modified by on ground management at the property level. The one exception is wind run.

Wind run drives evaporation which impacts on farm dams, soil moisture and thus on pastures. Wind run is the product of average wind speed and time and is closely tied to wind direction. A halving of average wind speed halves the wind run. Wind run and/or wind speed can be modified by the establishment of windbreaks. An attempt is made to estimate and quantify the local potential benefit of windbreaks in realistic and practical terms.

Windbreak Porosity, downwind Distance and Wind reduction

A model was developed to integrate data given in Cleugh (pp 14, 15, 17 & 21). The close linear fit between the model and Cleugh suggests that a high degree of confidence can be placed in the calculated values shown in **Table 1**. Downwind distances are expressed in terms of the unit ‘H’, the height of the windbreak.

The table indicates that an average 30% reduction in wind speed, and thus wind run, can be achieved with a medium (40 % porosity) windbreak out to 30 H and by a sparse (70 % porosity) windbreak out to 15 H. Given the feasibility of achieving a 30% average wind reduction over substantial downwind distances with even a sparse windbreak, this conservative value was used to examine the effect on evaporation and the potential local benefits to farm dams and pastures.

Potential Benefit to Farm Dams and Water Storages

Average modelled runoff rainfall (1986-2005) is 131 mm per year. The trend is a decrease at the rate of -108 mm per decade. Average annual evaporation loss at Braidwood is 988 mm (20 years, 1986-2005). The trend in annual total evaporation over the ten years 1996-2005 is an increase at the rate of +258 mm per decade. These trends indicate that not only is there less runoff to collect but more of it is being lost by evaporation from open water surfaces. This calls into question the adequacy of existing farm storage capacities.

Evaporation is sensitive to both maximum air temperature and to wind run. As shown in Figure 14 (page 13) on average 44% of evaporation can be attributed to wind run, and as shown in Figure 15, North-westerly winds account for most of the evaporation.

Table 1.

Wind speed reduction (%) provided by windbreaks of various porosities. Calculated point values and averages over various distances downwind expressed as multiples of the height (H) of the windbreak.
Derived from data extracted from "Trees for Shelter - A guide to using windbreaks on Australian Farms", Helen Cleugh (Ed), 2003.

Porosity (%)	Dense . 30		Medium . 40		. 50		. 60		Sparse . 70	
	REDUCTION in wind speed (%)									
Distance (H x)	@ point distance	average ≥0 H	@ point distance	average ≥0 H	@ point distance	average ≥0 H	@ point distance	average ≥0 H	@ point distance	average ≥0 H
0.0	39		30		24		21		19	
1.5	47	43	38	34	31	28	27	24	25	22
3.0	55	47	46	38	38	31	33	27	30	25
4.5	64	51	53	42	45	35	39	30	35	27
6.0	72	55	61	46	52	38	45	33	41	30
7.5	69	58	55	47	45	39	39	34	38	31
9.0	63	59	49	47	39	39	35	34	35	32
10.5	57	58	43	47	34	39	30	34	31	32
12.0	52	58	38	46	30	38	27	33	28	31
13.5	46	56	34	45	26	37	23	32	26	31
15.0	42	55	30	43	22	35	20	31	23	30
16.5	37	54	26	42	19	34	18	30	21	29
18.0	33	52	22	40	17	33	15	29	18	28
19.5	29	50	19	39	14	31	13	28	16	28
21.0	25	49	17	37	12	30	11	26	15	27
22.5	22	47	15	36	11	29	10	25	13	26
24.0	19	45	13	35	9	28	9	24	11	25
25.5	17	44	12	33	9	27	8	24	10	24
27.0	15	42	11	32	8	26	8	23	9	23
28.5	13	41	10	31	8	25	8	22	8	23
30.0	11	39	10	30	9	24	8	21	8	22

The model developed to split the effects of temperature and wind run was used to examine the effect of reduced wind run on evaporation. From Table 1, a wind reduction of at least 30% can be achieved with a sparse (70% porosity) windbreak at distances between 3 H and 11 H downwind. To simulate the potential benefit of an all-round windbreak shelter on an open water storage the measured monthly wind run in each of the 228 months 1987-2005 was reduced by 30%.

A 30% reduction in wind run resulted in an average reduction in evaporation of 23%, a saving of 222 mm per year, see Figure 16.

This is almost ten times the climate change annual increase in evaporation over the last decade.

Potential Benefit to Pastures

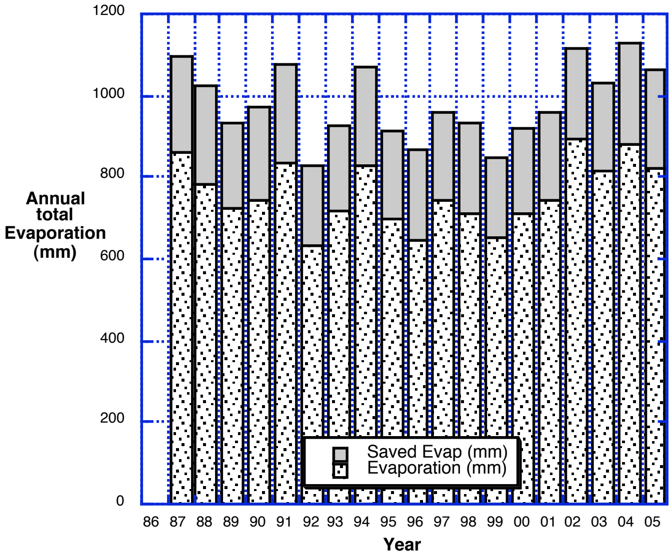
It should be noted that the climate change trend in grazed pasture carrying capacity is a decrease of 34.8% over the last twenty years.

Cleugh reports that wind shelter had little effect on the rate of transpiration (water use) by plants but that shelter reduced evaporation from the soil surface (while it was still relatively wet) and thus conserved water for use by plants later in the growing season (pp 28, 29).

A grassland version of Mount's Soil Dryness Index (SDI) has been in use for 20 years and is accurate to within plus or minus one mm between runoff events. The index is calculated daily and provides a reliable estimate of soil moisture conditions under pastures.

Figure 16.

Annual total EVAPORATION (mm, total column height) and modelled effect of reducing WIND RUN by 30% by windbreaks around a farm dam at Braidwood, 228 months 1987-2005.
Estimated average annual reduction in evaporation is 222 mm.

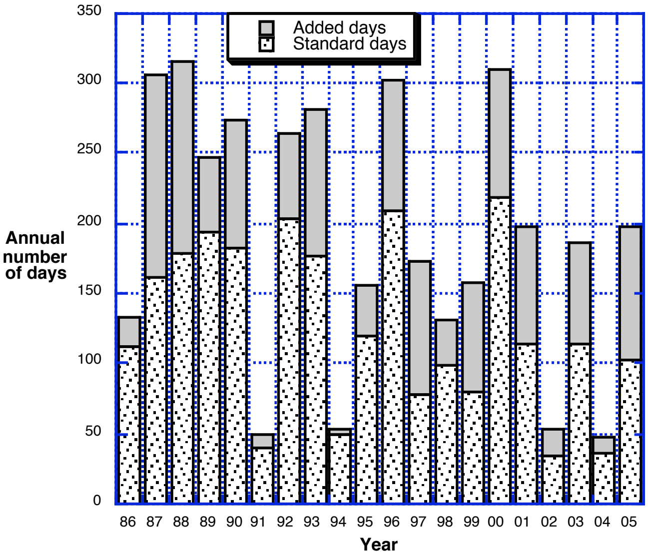


From local observation, pasture growth is slowed by low temperatures during the three winter months and by low soil moisture when the SDI is above 50 mm during the other nine months of the year. Mount describes how moisture loss is due to a combination of evaporation and transpiration up to an SDI of 50 mm and above that point loss is restricted to transpiration only. This is compatible with the findings reported by Cleugh.

A modified version of the Grassland SDI was used to model the effect of reducing wind by 30% during the nine months September to May each year. On those days when the SDI was less than 50 mm (and thus surface soil relatively moist) evaporation was reduced by a weighted average of 23% (as found above). This model was applied to daily maximum temperature and rainfall and compared with the 'standard' daily SDI for the 20 years 1986-2005. During the nine months September to May, the 'standard' model indicated an average of 125 days per year with an SDI of less than 50 mm.

Figure 17.

Annual frequency of DAYS in nine months September to May with a Soil Dryness Index (SDI) of less than 50 mm. Standard Grassland model and modelled effect of reducing WIND RUN by 30%, adds an average of 38 days per year.
Estimated for Braidwood, 20 years 1986-2005.



A reduction in wind run by 30% increased the average number of days per year with an SDI of less than 50 mm by 38 days or 30.4%, shown as "added days" in **Figure 17**.

It is evident in Figure 17 that the potential benefit of wind shelter is marginal in years with a low annual total rainfall (1994, 2002, 2004) and/or a dry spring season when most of the wind occurs (1991, 1994, 2002). On the other hand, the "added days" present more opportunities to conserve fodder. The 30.4% average increase in the annual number of days with soil moisture suitable for growth can be compared with the 34.8% decline in carrying capacity over the last twenty years.

Potential Benefit to Runoff

A by-product of modelling the effect on pastures of reducing wind run by 30% was a 26.4 mm (19.8%) increase in average annual runoff. The connection is that if soil is kept moister for longer it takes less rain to bring soil water to saturation resulting in greater and more frequent runoff. The effect on runoff within the area that is planted to windbreaks or shelter belts is more complex. Interception of rain by leaves within the tree canopy causes a reduction in the amount of rain reaching the ground surface and less runoff. Thus there is a gain / loss trade off.

If less than 16% of a catchment area were planted with windbreak trees at suitable intervals and orientation the result would be a nett gain in runoff compared to open unsheltered grassland.

Potential Benefit to Livestock

Wind chill is a result of a combination of cold, wet and windy conditions and causes cold stress on livestock which can kill lambs and adult off-shears sheep and suppress weight gain in cattle. Not only do the animals look miserable but feed conversion efficiency is reduced, more of what goes down their throat is used to keep warm.

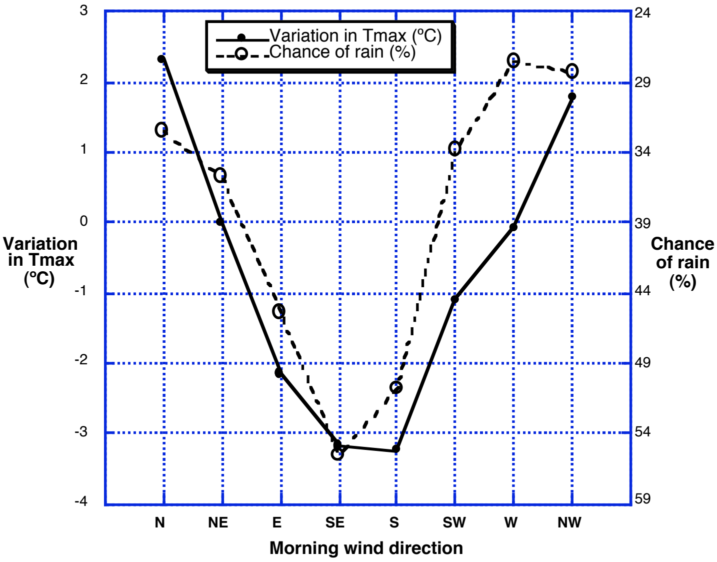
Our coldest winds come from the South and Southeast. These two directions also have the highest incidence of rainfall and thus present the greatest risk of wind-chill. The deviation of maximum temperature from long-term average and the relative frequency of rainfall in the 24-hour period following morning wind directions are shown in **Figure 18.** The rain frequency scale is inverted.

The three months with the lowest average temperatures are June, July and August. During these three months the average frequency of South and South-easterly winds is 17% of days. Of the 70 days with the highest wind run (highest average wind speed) in the 19 years 1987-2005, 35 (50%) were in July or August. Wind chill is a significant factor in animal productivity at Braidwood.

Though climate change is decreasing the frequency of South-east, South and South-west winds, cold stress on stock can be moderated by wind shelter.

Figure 18.

MAXIMUM (air) TEMPERATURE deviation from the long-term average (°C, solid line) and frequency of RAINDAYS (%, broken line), in the 24-hour period following morning WIND DIRECTIONS at Braidwood, relevant to cold stress on livestock, 20 years 1986-2005.
The rain frequency scale is inverted to assist comparison.



Design of Windbreaks

Orientation. The morning wind direction associated with the highest wind runs, the highest evaporation and the greatest impact on dams and pastures is North-west. Wind directions associated with the highest risk of cold stress on stock are South and South-east.

The ideal windbreak alignment is from Southwest to Northeast, at 90 degrees to North-westerly winds and also offering shelter to livestock.

Porosity. The months with the highest wind runs, and a disproportionate share of evaporation due to wind run, occur in late winter early spring. The months with the greatest risk of cold stress on livestock are in late winter.

Deciduous species offer the least wind protection when shelter is most needed. Evergreens offer year round protection.

Dual purpose. Many consider dual purpose in terms of drought fodder or firewood. Several varieties of European olive trees will grow in this climate. They are evergreen, relatively unpalatable to stock (which might involve less requirement for fencing), relative fast growing in the early years (contrary to urban myth), long lived, and with tree-shaker harvesting offer an alternative income source. I understand that there can be problems with the African olive becoming a weed (but not the European olive).

Getting started. There are numerous external funding sources. A non-profit organisation in Sydney is committed to planting thousands of trees and looking for farms on which to plant them - free. A non-profit carbon trading organisation is offering an ongoing income stream for tree planting and protection. All this and less water lost from farm dams and more productive pastures.

Conclusions

- There are records of adequate length to show that statistically significant climate change is occurring.

- There is a significant decline in the livestock carrying capacity of grazed pastures.

- There is are distinct links between climate change and declining livestock carrying capacity.

- Change in the wind pattern is a major factor in climate change at Braidwood.

- Of all the climate elements impacting on the carrying capacity of pastures, only wind is susceptible to on farm management - by the provision of windbreak shelter.

- It is calculated that a medium density windbreak (40 % porosity) can produce a 30% reduction in wind speed averaged over a downwind distance of 30 times the height (H) of the windbreak.

- It is calculated that a 30% reduction in wind by a windbreak around a farm dam can reduce annual evaporation by an average of 222 mm or 23%.

- It is calculated that a 30% reduction in wind could increase the number of days with an SDI of below 50 mm (soil moisture adequate for growth between September 1st and May 31st) by an average of 38 days per year or 30.4%.

- It is calculated that planting up to 16% of an open paddock with suitably oriented and spaced windbreaks could produce a nett increase in average runoff. For the pasture component, a 30% reduction in wind could increase annual runoff by an average of 26.4 mm or 19.8%.

- A windbreak that is oriented South-west to North-east to maximise shelter from North-westerly winds and reduction in evaporation will also provide livestock with significant shelter from South and South-easterly winds which are associated with the highest risk of cold stress.

- The evidence reported here suggests that field trials should be carried out in this district to investigate the economics of alley farming pastures between windbreaks (with and without protective fencing) at intervals and porosities suggested by the wind reduction figures in Table 1.

Index to key terms   Page numbers in italics refer to figures.

Acknowledgements

The late Jim Marsh, former postmaster at Braidwood, provided me with his entire collection of handwritten weather observation sheets and journals from which data prior to 1986 are drawn.

Accurate beef cattle numbers and the relevant land areas involved were provided by the owner / manager of a large beef cattle operation in the district who entrusted me with his private tally books and diaries on condition that the source and details remain confidential.

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