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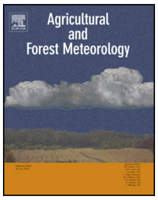

A simple parameterisation of windbreak effects on wind speed reduction and resulting thermal benefits to sheep

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ABSTRACT

It is well known that windbreaks can provide favourable conditions for livestock. Determining the benefit of any given windbreak system first requires that the impact of the windbreak on the wind microclimate is characterised, but in practice, modelling wind flow around obstacles is complex and computationally intensive. We report a simple parameterised model to estimate the wind speed reduction around a windbreak. Analytically, model parameters showed close links to the real-world attributes that characterise windbreaks. The model was validated with field measurements on a farmland in the UK; a Monte Carlo simulation was used to measure model parameter uncertainties. Results showed that the model produced an excellent fit to the relative wind speed (i.e. normalized by ambient wind speed) with root-mean-square error of 4% ± 0.5%. The model was further applied to literature data to characterise the dependence of the relative wind speed on windbreak porosity. A field-scale simulation of a sheep grazing system, including an explicit description of wind-chill effects, was conducted to estimate the net gain associated with including a windbreak in sheep productivity. The maximum productivity gain (27%) was found at a porosity of 0.5 and a wind speed of 12 m/s. Wind-chill effects were further simulated for lowland and upland environments, and related to ovine-specific thermal tolerance limits. Results showed a distinct response to reduced wind speeds between sites, indicating different levels of thermal risk to livestock and different, microclimate-specific, windbreak benefits for each location. The simplified models proposed in this study provides a generic framework for an efficient and precise quantification of windbreak effects and optimising the design of windbreak systems.

1. Introduction

Windbreaks or shelterbelts have been used in the agricultural landscape for centuries. In cold and windy environments, where potential negative aspects such as drought and stagnant air are insignificant, they are considered to have a generally positive effect on livestock productivity (Brandle et al., 2004; Grace, 1988). Windbreaks afford direct physical protection from a thermally stressful environment (Cleugh, 1998) as generated by high wind, sun and precipitation. Crucially for livestock production, the immediate microclimatic conditions determine energy balance and extent of energetic flux to the environment.

Energy generated by metabolism over and above requirements for vital processes, is, in agricultural systems ideally apportioned to production (i.e. weight gain), but in cold conditions is utilized in meeting the increased demands of thermoregulation (Bianca, 1976). When exposed to a cold and windy environment, the insulating boundary layer formed by fur, hair or fleece is diminished and convective heat loss from the body of the animal to the surrounding environment is thus increased (McArthur and Monteith, 1980a; Mount and Brown, 1982). The resulting decrease in temperature perceived by the organism as a result of this additional heat loss is commonly known as the wind-chill effect, meaning that under wind conditions, animals experience a colder condition than in still-air, and lower than the ambient temperature. Low-wind microclimates provided by windbreaks reduce heat loss and increase overall productivity (Ames and Insley, 1975; McArthur and Monteith, 1980b) as well as lowering lamb mortality (Pollard, 2006).

As endothermic homeotherms, ovines defend internal homeostasis, with a mean core thermal set-point of 39 °C (with a typical range of 37.9–39.8 °C (Bligh et al., 1965)). Within a narrow range of environmental temperature (thermo-comfort zone: TCZ, A-A' on Fig. 1), metabolic heat production is sufficient to balance the still-air energetic flux between animal and microclimate without requiring the initiation of additional thermoregulatory strategies. As the ther-

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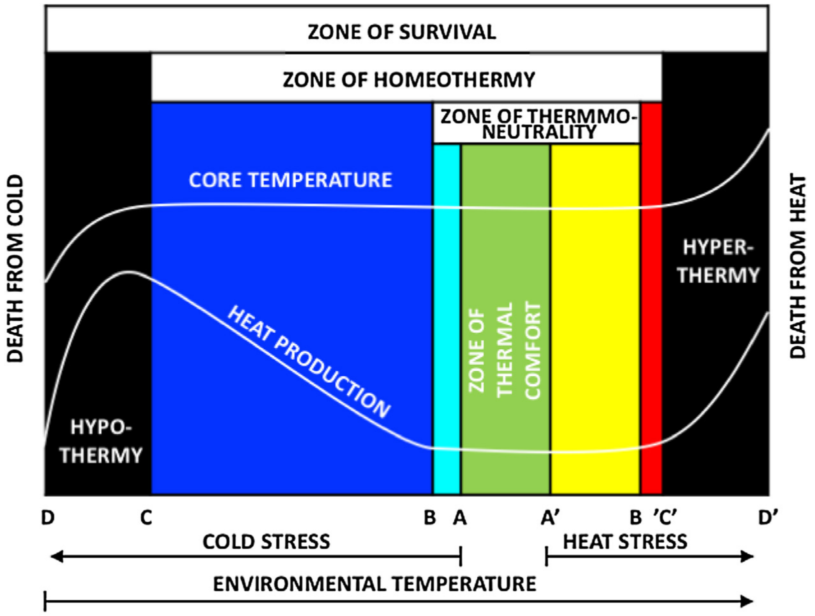

Index	Physiological Definition		Temperature (°C)
A	Zone of thermal comfort (TCZ)	Lower limit	8
A'		Upper limit	18
B	Zone of thermal neutrality (TNZ)	Lower limit	-3
B'		Upper limit	24
C	Lower critical temperature (LCT)		-10
C'	Upper critical temperature (UCT)		32
D	Death through hyperthermy		ND
D'	Death through hypothermy		ND

Fig. 1. Zones of thermal comfort (TCZ), neutrality (TNZ) and critical thermal limits illustrated graphically with equivalent temperatures for a temperate acclimatised adult ewe on maintenance diet with 50 mm of fleece shown below. Graph adapted from: (Bianca, 1968); Temperature

Source: (Bianca, 1971, 1968; Blaxter, 1962; CAgM report, 1989).

mal gradient between core body temperature and the environment increases, first behavioural, and then physiological, responses must be initiated to maintain core temperature, incurring an increased energetic cost. Animals experiencing temperatures outside the TCZ, but within thermo-neutral zone (TNZ, B-B'; Fig. 1) cease feeding and seek shelter or shade. Beyond the limits of TNZ, physiological changes to the animal's insulation properties and intensification of metabolic heat production, catabolism of tissue and shivering thermogenesis (cold temperature) or increase in evaporative heat loss through sweating or panting (high temperature) occur to meet the energetic cost of thermal stress. Once outside lower or upper critical temperature limits (LCT, UCT), probability of death by hypo- or hyperthermia is a direct product of accumulated time and temperature. The thermal limits for an adult sheep are detailed in Fig. 1.

It is intuitive, therefore, that farm planning should be conducted with consideration of the influence of microclimate on energetic balance and production, and providing outdoor raised livestock with shelter, such as windbreaks. However, the positioning of sheltering 'green infrastructure' such as hedgerows, shelterbelts etc. in the UK is often done either on an 'ad hoc' basis, based on farmer experience, intuition or convenience, or by re-establishing historical field boundaries. There is therefore a concern for scientific evidence-based advice in optimising 'weather-wise' farm planning.

Prior to studying the livestock thermal benefits to livestock created by windbreaks, it is fundamental to have a quantitative evaluation of the windbreak impacts on microclimate such as wind field, temperature and humidity. The impacts have been found to be significant in various environmental conditions (McDonald et al., 2007; Nord, 1991; Středa et al., 2011), however, this is generally a highly non-linear process that varies with inter-correlated environmental drivers such as windbreak types, air flow, solar radiation and rainfall. The aerodynamic properties of a windbreak determine its effectiveness in altering leeward microclimate, but due consideration must also be given of the characteristics of the object to be protected (Zhang et al., 1995). The aerodynamic properties of a living windbreak may also be affected by seasonal variation in structure (e.g. deciduousness) (Koh et al., 2014).

In the scientific literature, there have been many attempts to grapple with numerical simulations of the equations that govern windbreak aerodynamics (e.g. Bitog et al., 2012; Speckart and Pardyjak, 2014; Torita and Satou, 2007; Wang and Takle, 1995; Yusaiyin and Tanaka, 2009; Zhou et al., 2007, 2005). In addition to the technical problems of solving these partial differential equations (e.g. how to discretize the equations and choose an appropriate grid size), a fundamental obstacle to using these models in the field is that they are typically derived from wind tunnel experiments that are necessarily simplified and unrealistic given the complexity of a real windbreak (i.e. one made up of flexible and irregularly-shaped trees and leaves). Moreover, the procedure of implementing such simulations is computational intensive and is cumbersome to apply to any real-world scenario. In short, there is a need for a simple parameterized model, based on real-world observations, that can provide not only a computationally-efficient estimation of the wind speed reduction around a real windbreak, but also the follow-up quantification of the effects of that windbreak on livestock productivity. Several previous researchers have