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Microclimate drives shelter-seeking behaviour in lambing ewes

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Abstract: Silvopastoral agroforestry and the strategic placement of trees and hedgerows offers potential to improve livestock wellbeing and production efficiency through the provision of shelter in livestock farming systems. The aim of this study was to investigate the relationship between shelter-seeking behaviour of ewes during the lambing period and the microclimate influenced by landscape shelter features. Artificial and natural shelter was provided to Aberfield ewes (n=15) on an upland sheep farm that were continuously monitored for 14 days using global positioning system tracking devices. Modelling of microclimate influenced by topographical shelter features at the test site was used to generate a 1-m resolution wind field for geospatial statistical analysis of localised wind speed. Ewes demonstrated a statistically significant preference for both natural and artificial shelter, when compared to the exposed area of the trial site. Wind-chill and modelled local-scale wind speeds were found to have the greatest influence on shelter-seeking behaviour, with temperature and field-scale wind speed significantly altering livestock behaviour. Mean wind-chill temperature during the trial was 3.7 °C (min -5.3 °C; max 13.1°C), which is within the cold stress temperature threshold (-3 and 8 °C) that requires thermoregulatory strategies such as shelter-seeking behaviour. An agent-based model was developed to demonstrate shelter-seeking behaviour in sheep and the energetic benefits of tree shelter to stakeholders.

Keywords: Silvopasture; Agroforestry; Sheep; Shelter; Agent Based Model

Citation: Atkin-Willoughby, J.; Hollick, S.; Pritchard, C.E.; Williams, A.P.; Davies, P.L.; Jones, D.; Smith, A. *Forests* **2022**, *13*, x. https://doi.org/10.3390/xxxxx

Academic Editor: Firstname Lastname

Received: date
Accepted: date
Published: date

1. Introduction

Silvopastoral agroforestry is a practice that integrates trees and hedgerows into livestock farming systems [1]. These agroforestry systems are often framed as *win-win* scenarios that promote livestock welfare and productivity [2,3], whilst also providing environmental benefits, such as climate change mitigation, hydrological regulation and biodiversity gains [4,5].

In the UK and New Zealand, 10 to 15% of newborn lambs die each year through cold exposure [6], and extreme weather events have been documented to accelerate these losses [7]. However, a silvopasture experiment integrating hedgerow shelter into pasture, conducted in New South Wales, Australia, showed that lamb mortality in a sheltered environment was half of that in a exposed paddock [2]. More recently, the benefits of shelter provision to sheep welfare was demonstrated through a reduction in shepherding interventions, such as ewe dystocia and lamb mortality [3]. A systematic review of the productivity and environmental impacts of temperate agroforestry and ruminant livestock identified only 14 articles in both the grey and peer-reviewed literature [8], suggesting that the scientific evidence-base around livestock productivity and welfare in silvopasture is poorly understood.

Sheep (*Ovies aries*) maintain homeostasis through metabolic heat production, with a narrow range of ambient temperature (i.e., 8 to 18 °C) known as the thermocomfort zone (TCZ). Ambient temperatures outside of the TCZ and between -3 and 24 °C are defined as the thermoneutral zone (TNZ) [9], where sheep exhibit shelter-seeking behaviour. Beyond the TNZ, regulatory changes in metabolic heat production (e.g., thermogenesis via shivering) occur to meet the physiological demands of cold stress. This effect is amplified by combinatory weather variables such as wind speed, low temperatures that when combined produce colder than still air conditions (i.e., wind-chill) and rain, which reduces the insulating properties of sheep fleeces [10-12]. Consequently, newborn lambs can be vulnerable to death from hypothermia when still covered in amniotic fluid, or born at a low weight, which reduces the thermoregulatory capability of the animal [13].

In inclement weather, it is well-known that sheep seek the sheltered zone created by wind breaks [14], which lie in the eddy of the upwardly deflected air and can persist up to a distance of 14 times the height of the shelter [15]. The effect of shelter establishment on local-scale microclimate varies according to the topography and aspect of the field, and environmental conditions change spatially and temporally [16]. The extent of shelter is also affected by physical characteristics of the windbreak, such as the porosity, height and depth [17]. Whilst a substantial body of evidence exists to describe the physical effects of windbreaks on microclimate, few studies have explored the utilisation of windbreak shelter by livestock in agroforestry systems [18].

Early research into British hill sheep (Scottish Blackface ewes) established an increased likelihood of shelter-seeking behaviour in progressively worsening weather, with a change in ewe behaviour in wind speeds above 11 m s^{-1} and temperature was below freezing [14]. This contrasts with more recent work describing Merino ewes in Australia, whereby sheltering has been observed around 13 °C [18], highlighting the variability between breeds in different countries. Furthermore, the phase of the production cycle can also influence shelter-seeking behaviour, such as whether the ewe is lambing [19]. It has also been shown that the upper TNZ threshold increased by 10 °C after a sheep was recently shorn [20,21]. Finally, the utilisation of shelter can be influenced by external factors, such as anthropogenic disturbance (e.g., road noise and human proximity) [22] and predation threat that is evidenced by habitat selection based on security from predators and vegetation offering greater thermal comfort [23].

Research regarding the utilisation of shelter by sheep has largely focused on Merino ewes in Australasian systems, where shelter-seeking behaviour has been demonstrated through the use of Global Positioning System (GPS) collars [15,19]. One such study employed GPS collars to investigate the usage of a combination of two shelter types, hedgerows and shrubs, and ewes bearing twin or single lambs [24]. Despite a lack of shelter utilisation before and after lambing, the study found ewes preferred to lamb close to the shelter, which the authors argue was due to the lower wind-chill and windspeeds in the sheltered zone. A similar study tracked Merino ewes using GPS collars to observe significant utilisation of individual trees and field perimeter shelterbelts [18]. Shelter-seeking behaviour in Merino ewes was observed up to a month after shearing, suggesting that the sheep may have a greater sensitivity to weather conditions following fleece removal than is currently understood. Despite GPS devices being used in approximately half of all on-animal sensor sheep research [25], there has been limited application of GPS systems in the investigation of shelter utilisation by sheep [18], with none to date in a British context.

Recent reviews of the effect of windbreaks on livestock production highlighted the importance of understanding livestock response to shelter in various environmental conditions, noting a particular lack of research focused on natural shelter, such as trees and hedgerows [26]. Here, we build upon earlier work [3], using the same study site to investigate the associated drivers of shelter-seeking behaviour in Aberfield ewes. Our overarching aim was to investigate the relationship between shelter-seeking behaviour of lambing ewes and microclimate influenced by landscape shelter features. We hypothesized that: (i) shelter-seeking behaviour is being displayed by the ewes for both artificial and natural shelter; (ii) wind speed, temperature, or the derived effective temperature index wind-chill drives shelter-seeking behaviour in ewes; and (iii) Landscape topography (slope) affects shelter-seeking behaviour. A greater understanding of the relationship between microclimate and shelter-seeking behaviour in sheep will improve the evidence-base to support a move towards silvopastoral agroforestry and farming practices that benefit farm productivity, livestock welfare and the environment.

2. Materials and Methods

2.1. Study site

The study was conducted at a commercial sheep farm, in Ceredigion, Wales (52°27′26.298″N, 3°57′55.195″W) during April 2019. In this work, data generated from an exposed 'test' field containing limited and broken bands of hawthorn (*Crataegus monogyna*) around the field margins was used (Figure 1). For a description of the trail field and artificial and natural shelter (Table 1), see Pritchard et al. 2021 [3].

Table 1. Description of artificial shelters, shape, physical dimensions, and optical porosity used to evaluate the shelter-seeking behaviour of sheep. Reproduced from Pritchard et al. 2021 [3].

Name	Shape	Height (m)	Length (m)	Breadth (m)	Optical Porosity (%)
Shelter 1	Elongated S	0.7	16.5	5.5	0.05
Shelter 2	Cross	0.7	8.0	7.5	0.05
Shelter 3	Elongated S	0.7	26.5	8.5	0.05

Figure 1. Satellite image of the study area demonstrating natural and artificial shelters © Getmapping Plc.

2.2. Climate and microclimate parameters

To measure the ambient weather conditions, an automatic weather station (AWS; Vantage Pro 2, Davis Instruments, USA) was installed at the northern-eastern field boundary. The AWS recorded wind speed, wind direction, air temperature, rainfall and relative humidity in 30-minute intervals between March and April 2019, which was a notably mild spring season (Table 2). A wind-chill index was calculated according to Campbell Scientific (2001) using Equation 1 where T = temperature, and WS = wind speed. The effect of the artificial shelters on wind speed was assessed using 2D WindSonic anemometers (Gill Instruments, Hampshire, UK) located on the leeward and windward sides of the shelter. As a result of the shelter, mean windspeed was reduced two-fold 0.35 m northwards of shelter 3 [3].

$$\boldsymbol{Wind\ Chill} = \mathbf{13.127 + 0.6215T - 13.947\ WS^{0.16} + 0.486T\ WS^{0.16}} \quad (1)$$

Table 2. Weather conditions (± standard error ; SE) at experimental site during the study period.

Weather variable							
Temperature (°C)		**Wind-speed (m/s)**		**Rain (mm)**		**Wind-chill (°C)**	
Mean	6.18 ± 2.91	Mean	3.73 ± 2.29	Total	144.2	Mean	3.69 ± 3.69
Minimum	0.6	Minimum	0	Daily Average	10.3 ± 18.62	Minimum	-5.3
Maximum	13.1	Maximum	9.8			Maximum	13.1

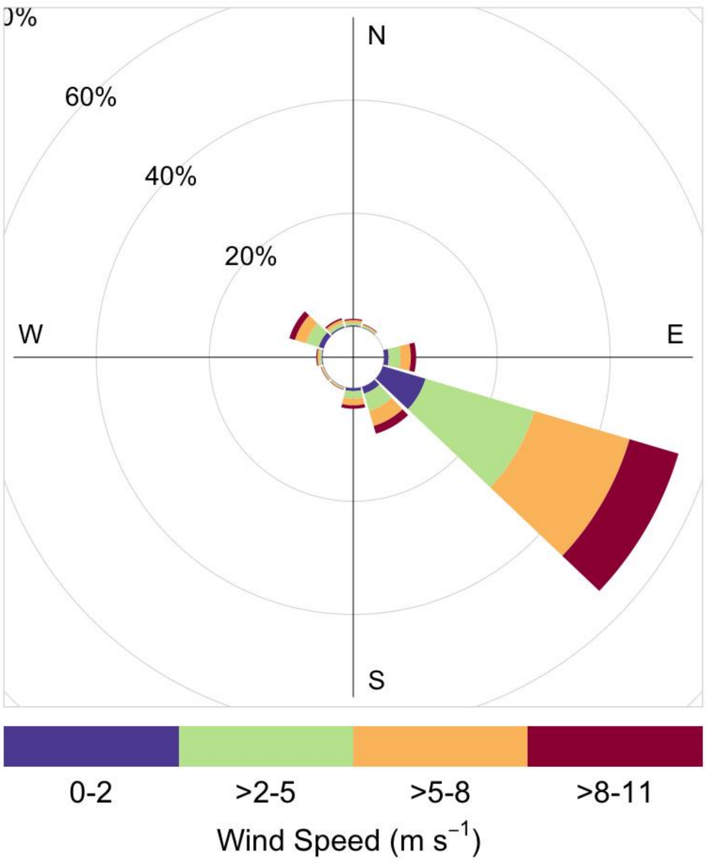


Figure 2. Predominant wind direction and speed during the study period (constructed using Open Air package, R Studio version 1.1.463).

2.3. Animals and GPS collars

The individuals selected for this study were all Aberfield ewes (n=15), aged between 4-10 years old, with a body condition score of greater than 3 (applying the 1-5 scale [27]), and an average weight of 66 kg. To track the spatial movement of individual animals with the trial, each individual was marked using spray paint to produce a coloured bar-code used for visual identification (VID) and tagged with an electronic identifier (EID). A subset of 7 individuals were tracked using GPS devices (Gipsy 6, TechnoSmart, Rome, Italy) mounted onto lightweight collars that recorded sheep longitude and latitude in 5-minute intervals throughout the study period (total 16,000 positions).

2.4. Spatial parameters

The location of individual sheep were imported into ArcMap (ArcInfo Desktop version 9.3; ESRI, CA, USA) and overlayed onto a satellite image of the trial field (Getmapping Plc 2021). A zone of shelter influence was calculated as 2.5 and 5 times the height (2.5H and 5H) of the shelter [15, 28] and a polygon drawn around the shelters using ArcMap to facilitate further analysis.

2.5. Modelling of the wind field

To model the wind field across the study site, Digital surface model (DSM) and digital terrain models (DTM) were obtained from Natural Resources Wales [29] at 1 m resolution, and a canopy height model (CHM) was derived from the difference between these models. An approximate wind field was calculated using the windcoe function from the microclimate R package [30], giving the effect of topographical shelter across the study site. The output from this analysis was a raster of values of shelter ratio (the ratio of local-scale windspeed over field-scale wind speed as recorded by the weather station) on the 1 x 1 m resolution of the DSM.

The effect of the artificial and natural shelter features on this approximate wind field were manually digitised as spatial polygons in QGIS (QGI.org 2021) using satellite imagery from Google [31]. Height values were attributed to each natural shelter feature by extraction from the CHM using the zonal statistics tool and selecting the maximum value. The attributed values for height of the artificial structures were recorded in the intitial study at the same site [3] (Table 1). Construction of a raster of shelter ratio values based upon the effect of these shelter structures was performed by calculating the shelter ratio at a series of 1000 random points and interpolating this result across the study site.

The shelter ratio at each point was modelled using an existing model [28] (Equation 1; Table 1) and assuming a dense vegetation (i.e. porosity of 0.36) representative of the gorse typically found at the field site. Interpolation of the wind field was performed using universal kriging with the krige function from the gstat R package [32,33]. The construction of the shelter ratio wind field raster was repeated by iterating over 16 principle compass directions (N, NNE, NE, NEE, etc). Finally, to calculate the local-scale wind speed variable for use in hotspot analysis, each field-scale wind speed record value (measured by the AWS) in the ewe GPS-weather dataset was multiplied by the grid cell shelter ratio corresponding to the recorded location and wind direction.

2.6. Statistical analysis

Four approaches were used to assess the shelter-seeking behaviour of ewes: (i) Preference Index (PI) was used to establish if sheep displayed a preference for sheltered areas; (ii) Moran's *I* was used to investigate spatial autocorrelation (i.e., overall clustered or dispersed pattern) for the input variables temperature, wind-chill and wind speed; (iii) hotspot analysis identified if significant spatial clusters of cold and hotspots of temperature, wind speed and wind-chill existed; (iv) Pearson spatial correlation testing slope as an explanatory variable of the hot/colds spots discovered during the hotspot analysis. All statistical analyses and figures were completed and constructed with R (R Core Team 2020; RStudio version 1.1.463, packages: ggplot2, tidyverse) and ArcMap (version 10.8.1; ESRI, CA, USA) with $p < 0.05$ used as the limit for statistical significance.

2.6.1. Preference Index

A PI value was calculated according to the methodology established in similar studies [24] (Equation 2) to establish if sheep exhibited a preference for sheltered or exposed areas (a value > 1 indicated a preference for that site):

$$PI = \frac{Proportion\ of\ time\ spent\ in\ area\ of\ interest}{Proportion\ of\ area\ relative\ to\ entire\ area\ available} \quad (2)$$

For each of the shelters and exposed areas, the 'count points in polygon' from the ArcMap toolbox was used to count the total time (number of 5-minute interval points) for each sheep in each area. This total (frequency) was then divided by the total frequency for each sheep. The same polygons were used to calculate exact area of each region and total site, using the field calculator function in ArcMap.

Significant difference in PI between sheltered and exposed areas was tested using a one-factor ANOVA with shelter zones as factors and PI as independent variables. PI data was assessed for normality using the Shapiro-Wilk test and homogeneity of variance using Barlett's test. Due to the violation of the assumption of equal variances, an ANOVA with Welsh's correction was used.

2.6.2. Spatial Autocorrelation Moran's *I*

Global Moran's *I* statistic was used to investigate the spatial autocorrelation (e.g. overall clustered or dispersed pattern) for input variables, temperature, wind-chill and local and field-scale windspeed. A positive Moran's *I* statistic (Moran's Index, on a scale of 0-1) indicates a clustering of high/low values, i.e. clustering of sheep positions when temperature was warmer or colder. The calculation applied for spatial analysis in ArcGIS is documented by ESRI [34].

2.6.3. Hotspot (Getis-Ord Gi*) Analysis

Weather data was restructured to match the 5-minute intervals of the GPS data, and GPS data were cleaned by excluding anomalous data points that lay outside the study area. This final weather and GPS dataset was then overlaid onto a 10 m x 10 m grid, which was merged using the 'merge' tool in ArcMap to provide a 10 m stratification of the GPS-weather dataset. Further temporal stratification was achieved using ArcMap's filter and split functions, to divide these data into 8-hour windows, which was then used for hotspot analysis.

Presence of statistically significant spatial clusters of cold and hotspots for temperature, wind-speed and wind-chill, was determined using the hotspot analysis (Getis-Ord Gi*; [35] function of ArcMap. The Gi* statistic relates a z score for each of the polygons of the stratified 10 m grid with a large positive z score relating to a hotspot and a large negative z score showing a cold spot. Scores are segregated into Gi* bins, with each bin representing varying degrees of confidence in statistical significance (Figure 3).

2.6.4. Parameters applied in Moran's *I* and Hotspot Analysis

To select the appropriate conceptualisation of spatial relationships and neighbour distance band, the 'incremental spatial autocorrelation' tool, in the analysing patterns toolkit in ArcMap, was used to investigate spatial clustering at set distances. Distances were tested at 5 m intervals between 1-100 m for input variables wind-chill, wind-speed and temperature. To ensure the minimum number of neighbours for each feature, a 10 m distance band was selected for testing both spatial autocorrelation and the presence of hot/cold spots.

An inverse-distance method conceptualisation of spatial relationships was chosen for both spatial autocorrelation and hotspot analyses, due to the potential greater likelihood of nearby features (sheep positions) to be interactive and effect each other, with Euclidian distance used. Likewise, due to the potential for spatial dependency in the GPS point data, the False Discovery Rate (FDR) correction was applied during the hotspot analysis, which acts by reducing the critical z-scores and p-values.

2.6.5. Spatial correlation of slope and hotspot analysis

To compare the explanation of microclimate driven shelter-seeking behaviour with an alternative hypothesis, of ewe clustering determined by slope of terrain. Correlations were performed between the raster of z values from the hotspot analysis, selecting only data records where the wind direction was the modal value (SE), and the shelter ratio raster for this wind direction and the terrain slope raster respectively. Each of the raster inputs were resampled on the same resolution as the raster of z scores, and vectors of the respective rasters values taken as the arguments for the *cor.test* function in R.

2.7 Agent Based Model

An agent based model (ABM) was constructed using NetLogo [36] to illustrate the shelter-seeking behaviour of sheep using established cold stress thresholds [28]. Input parameters included the amount of shelter (represented as brown patches) and the weather conditions (temperature, wind speed and wind direction). Sheep flocking behaviour was adapted from the existing NetLogo flocking model [37]. The energy of each agent is set to a random number between 80 and 90 to simulate natural variation in animal live weight and condition. The energy of each agent is then altered depending on weather conditions and proximity to shelter where each agents' energy is increased by 1 when it is in homeostasis within the TCZ (i.e., grazing in good weather) up to its initial value. If the agent is located near to shelter the wind-chill temperature is effectively increased by 10 °C due to the effect of shelter. Energy is decremented by 1 when the agent is in thermogenesis experiencing wind-chill temperatures between the TCZ and TNZ (i.e, wind-chill between 8 and -3 °C) and decremented by 2 when in homeothermy (i.e., experiencing wind-chill between -10 and -32 °C). When an agent's energy reaches 20 it's colour changes to blue, followed by red as the energy reaches 10, agents 'die' of hypothermia and are removed when total energy reaches zero.

3. Results

3.1. Ewe area preference (PI)

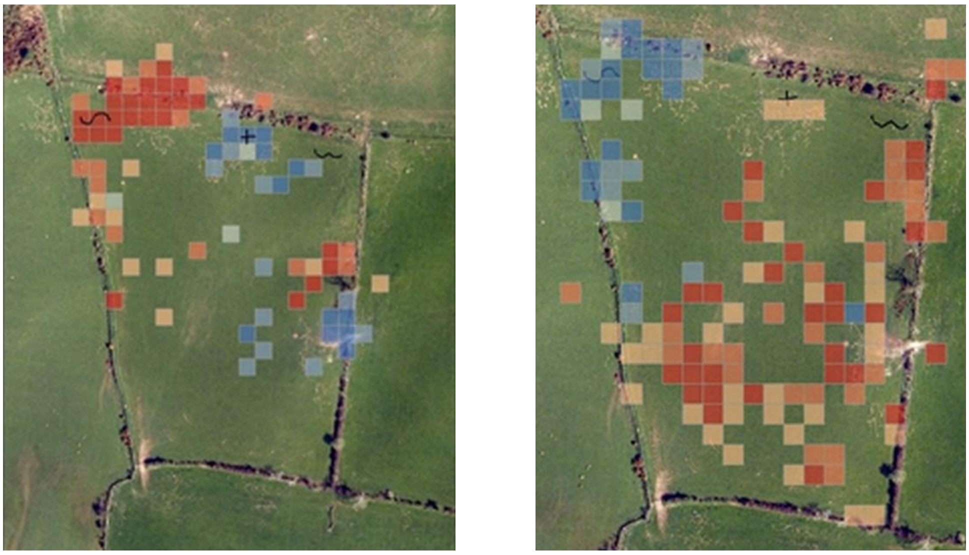
Ewes demonstrated a statistically significant preference for positioning themselves within the zone of shelter influence (i.e., a distance of 2.5H from the shelter) for shelter 1 ($P < 0.05$) compared with the exposed area of the trial site (Table 3). Whilst a similar PI was recorded for both the natural shelter and shelter 1 at 2.5H (PI = 4.6), the natural shelter did not significantly differ from the exposed area. This was also true for both artificial shelters 2 and 3 at 2.5H. Whereas, when calculated using shelter areas of 5H, significant differences did occur between both the natural shelter ($P < 0.01$), shelter 1 ($P < 0.05$) and the exposed field, again revealing a preference for these sheltered areas of the field. A lack of utilisation of the third artificial shelter was recorded using a 5H parametrisation, with the PI significantly differing from shelter 1 ($P < 0.01$).

Table 3. Ewe preference Index values for zones defined using 2.5 and 5 times the shelter height to define the sheltered region and the exposed area of the trial field. Data are mean ± SE with superscript letters indicating statistically significant ($p<0.05$) difference between areas.

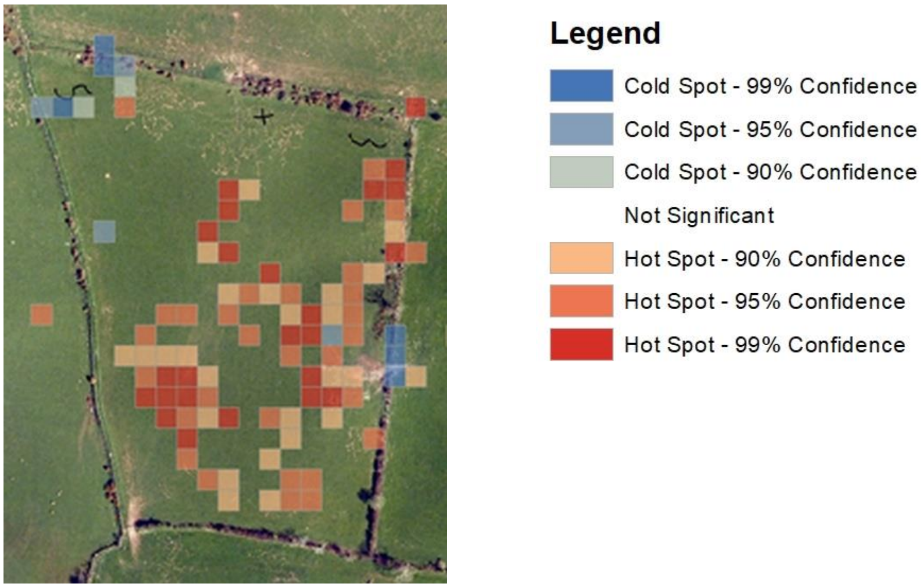
Distance	**Preference Utilisation Areas**				
	Shelter 1 (S)	Shelter 2 (+)	Shelter 3 (W)	Natural Shelter	Exposed Area
2.5H	4.605^{a} (± 3.804)	2.176 (± 2.329)	1.626 (± 1.889)	4.660 (± 3.318)	1.459^{a} (± 0.341)
5H	4.361^{bc} (± 2.002)	1.013 (± 2.316)	0.563^{c} (± 0.471)	4.944 ^{a} (± 2.567)	1.458^{ab} (± 0.551)

3.2. Hotspot analysis (Getis-Ord Gi)*

Application of Getis-Ord statistics revealed the presence of significant hot and cold spots for all 3 weather variables analysed (Figure 3), with a clustering of high values for wind-speed and low values for both temperature and wind-chill ($P < 0.01$) in the north-western portion of the study site, surrounding artificial shelter 1 and the natural shelter. Furthermore, hotspots for both temperature and wind-chill were distributed throughout the exposed region of the field ($P < 0.05$), with a small cluster of low temperature cold spots on the eastern hedgerow of the field ($P < 0.01$). Similar cold spots on the perimeter of the field were found for wind-chill on the western boundary of the site ($P < 0.01$). No hot or cold spots were found to correspond to supplementary shelters 2 or 3.



(A) (B)



(C)

Figure 3. Getis-Ord Gi* Hotspot Analysis for A) Wind-speed B) Wind-chill C) Temperature. For associated z scores see Table 4.

Table 4. Z scores relating to the significant hot and cold spots from the Getis-Ord Gi* Analysis (Figure 3).

Hotspot Analysis Output			**Weather variable**					
Figure colour	Hot/cold Spot	Confidence Interval	Wind speed z score range		Wind-chill z score range		Temperature z score range	
			Lower	Upper	Lower	Upper	Lower	Upper
	Cold	99% Confidence	-3.25	-8.88	-3.38	-7.52	-3.34	-6.31
	Cold	95% Confidence	-2.45	-2.87	-2.58	-3.15	-2.65	-3.01
	Cold	90% Confidence	-2.15	-2.39	-2.28	-2.47	-2.30	-2.43
	Hot	90% Confidence	2.12	2.49	2.16	2.49	2.28	2.60
	Hot	95% Confidence	2.5	3.14	2.53	3.13	2.64	3.29
	Hot	99% Confidence	3.15	8.15	3.15	5.37	3.33	4.91

Stratification of the GPS-weather dataset in to 8-hour intervals produced a similar effect to analysis of the whole dataset. With a clustering of high values for windspeed in the north-western corner of the field, around the natural shelter and artificial shelter 1 ($P < 0.01$) (Figure 4). However, stratification did reveal spatial clustering varied across a 24-hour period, with a greater proportion of hot and cold spots present during the morning (00:00 – 08:00), relative to the daytime (08:00 – 16:00) and the evening (16:00 – 23:59) (Figure 4-A).

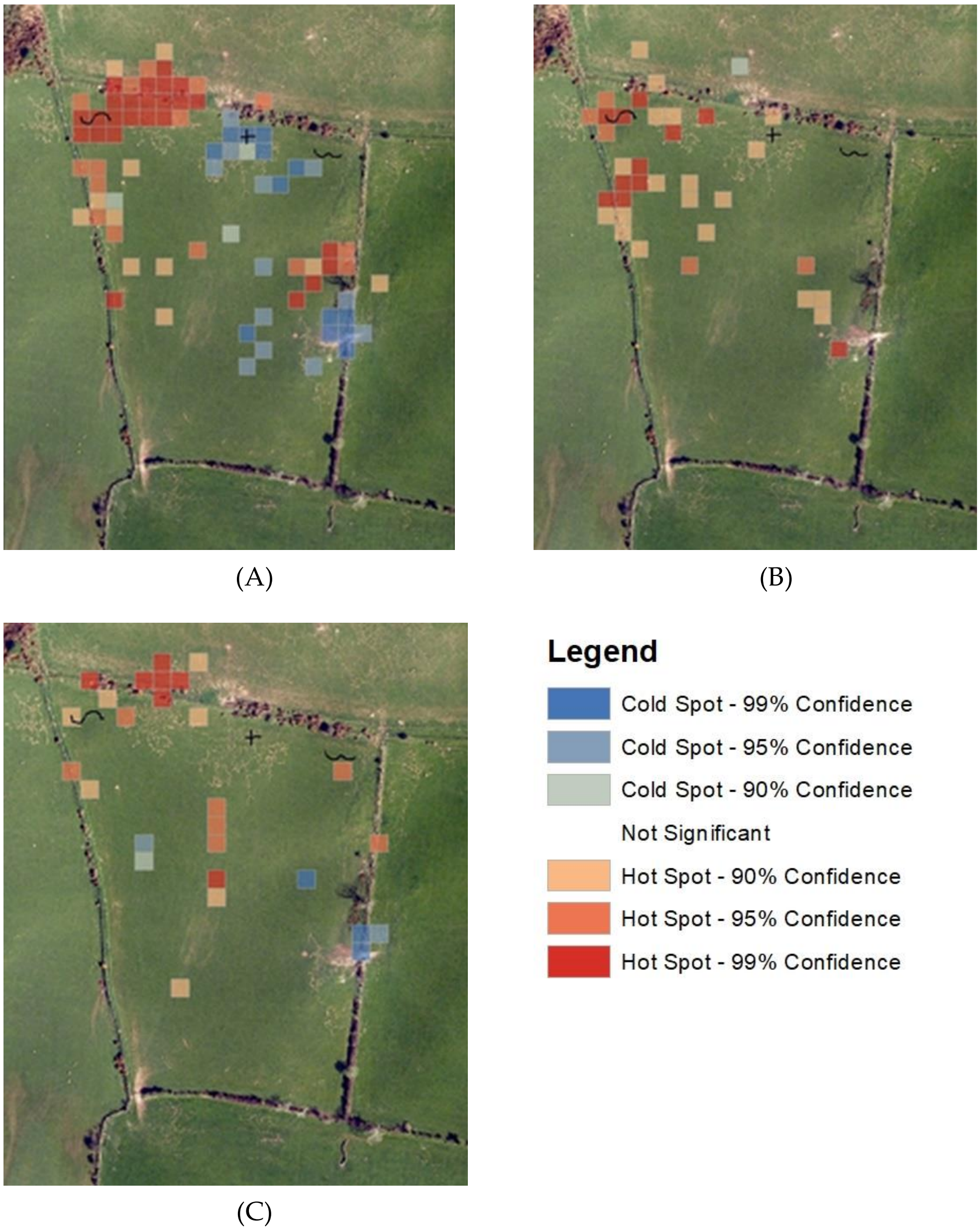


Figure 4. Getis-Ord Gi* Hotspot Analysis of wind speed during 8 hour windows (A) 12 pm - 8 am (B) 8 am - 4 pm (C) 4 pm - 12 pm. For associated z scores see Table 5.

Table 5. Z scores relating to the significant hot and cold spots from the Getis-Ord Gi* Analysis (Figure 4)

Hotspot Analysis Output			Weather variable					
Figure colour	Hot/cold Spot	Confidence Interval	Wind speed 12pm - 8am z score range		Wind-chill 8am - 4pm z score range		Temperature 4pm - 12pm z score range	
			Lower	Upper	Lower	Upper	Lower	Upper
	Hot	99% Confidence	2.95	7.75	3.48	5.20	3.29	5.39

	Hot	95% Confidence	2.35	2.93	2.92	3.02	2.75	2.97
	Hot	90% Confidence	1.99	2.24	2.48	2.88	2.42	2.61
	Cold	90% Confidence	-2.05	-2.21	-2.89	~	-2.48	~
	Cold	95% Confidence	-2.34	-2.94	~	~	-3.00	-3.18
	Cold	99% Confidence	-2.96	-4.38	~	~	-3.66	-4.99

3.3 Spatial autocorrelation (Moran's I)

Results of global spatial autocorrelation (Moran's *I*) analysis indicated that a statistically significant clustered pattern ($P < 0.01$) exists for sheep locations according to temperature, wind-chill and windspeed (Table 6). This effect was consistent when the dataset was tested as a whole, or temporally stratified in to 8-hour windows. The greatest degree of clustering (highest Moran's *I*) during analysis of the whole dataset was recorded for localised wind speed, followed by wind-chill (Table 6). In fact, spatial autocorrelation analysis of local-scale windspeeds, which are specific to the exact position of the animal, as aposed to the field-scale windspeed recorded by the AWS, results in more than doubling in the Moran's *I* (from 0.079 to 0.165).

Stratification of the dataset in to 8-hour windows resulted in an increase in Moran's *I*, which was consistent across all input weather variables, with the only anomalous exception being wind-chill during the 00:00 – 08:00 period. However, this effect was associated with a decrease in z-scores when compared to spatial autocorrelation for the whole dataset. Analysis of global spatial autocorrelation supports the local-scale hotspots identified through the Getis-Ord Gi* statistics (hotspot analysis), by showing a significant clustering for microclimate components across the whole study area.

Table 6. Summary of significant Moran's *I* values for the weather variables wind speed, wind-chill and temperature at various temporal scales.

Weather variable	**Time period**	**Moran's Index**	**Expected Index**	**Variance**	***z*-score**	**p value**
Wind speed						
Field-scale	24 hours	0.079139	-0.000086	0.000002	58.604481	< 0.01
	12 pm - 8 am	0.208103	-0.000237	0.000013	57.061155	< 0.01
	8 am - 4 pm	0.081247	-0.00025	0.000016	20.46512	< 0.01
	4 pm - 12 pm	0.087868	-0.000023	0.000023	18.529923	< 0.01
Local	24 hour	0.164785	-0.000086	0.000002	121.960344	< 0.01
Wind-chill						
Field-scale	24 hours	0.104977	-0.000086	0.000004	51.748428	< 0.01
	12 pm – 8 am	0.079546	-0.000237	0.000013	21.853108	< 0.01
	8 am -4 pm	0.150231	-0.00025	0.000016	37.788511	< 0.01
	4 pm - 12 pm	0.108544	-0.000023	0.000023	22.876377	< 0.01
Temperature						
Field-scale	24 hours	0.053609	-0.000086	0.000002	58.911145	< 0.01

12 pm - 8 am	0.100169	-0.000237	0.000013	27.501695	< 0.01
8 am - 4 pm	0.162655	-0.00025	0.000016	40.906711	< 0.01
4 pm - 12 pm	0.142596	-0.000023	0.000023	30.0343	< 0.01

3.4. Wind field model

The wind field documents reductions in wind speed to below 0.4 of the field-scale, weather station recorded values, with these sheltered areas being associated with the observed shelter structures (Figure 5). Greater wind speed reductions (i.e. lower values of shelter ratio) are predicted closer to natural shelter then are seen immediately adjacent to the 3 small artificial shelters. Further investigation of spatial correlation revealed a greater association between z score values from the hotspot analysis of windspeed and the localised wind field ratio outputs (0.21; Table 7), when compared to slope (0.05), with both explanatory variables revealing significant correlations (p-value < 0.01).

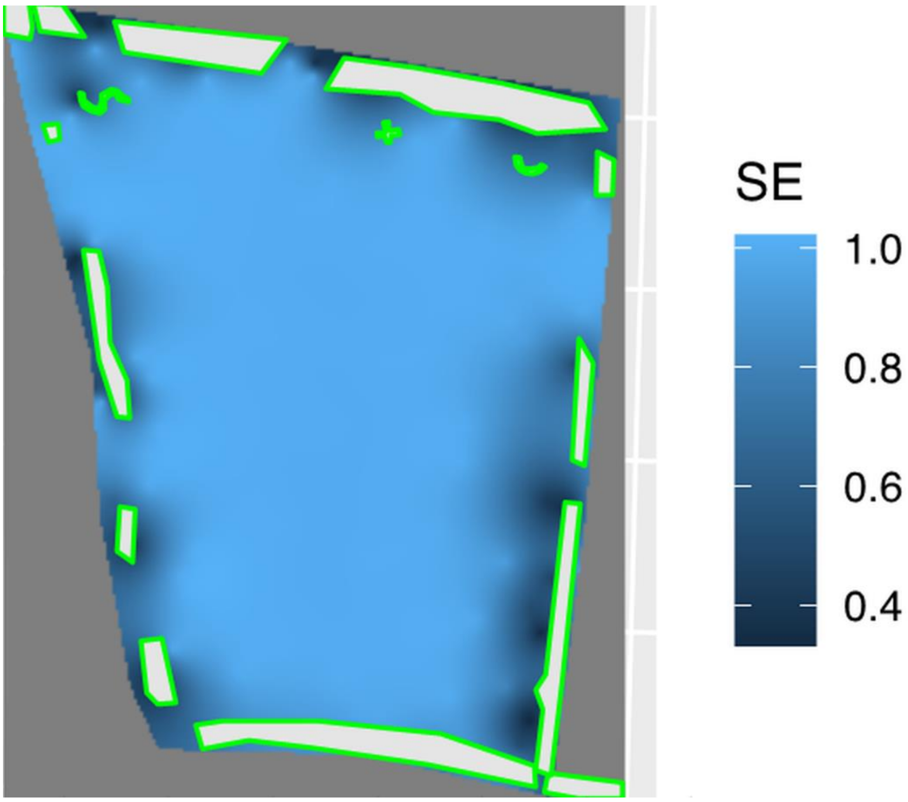


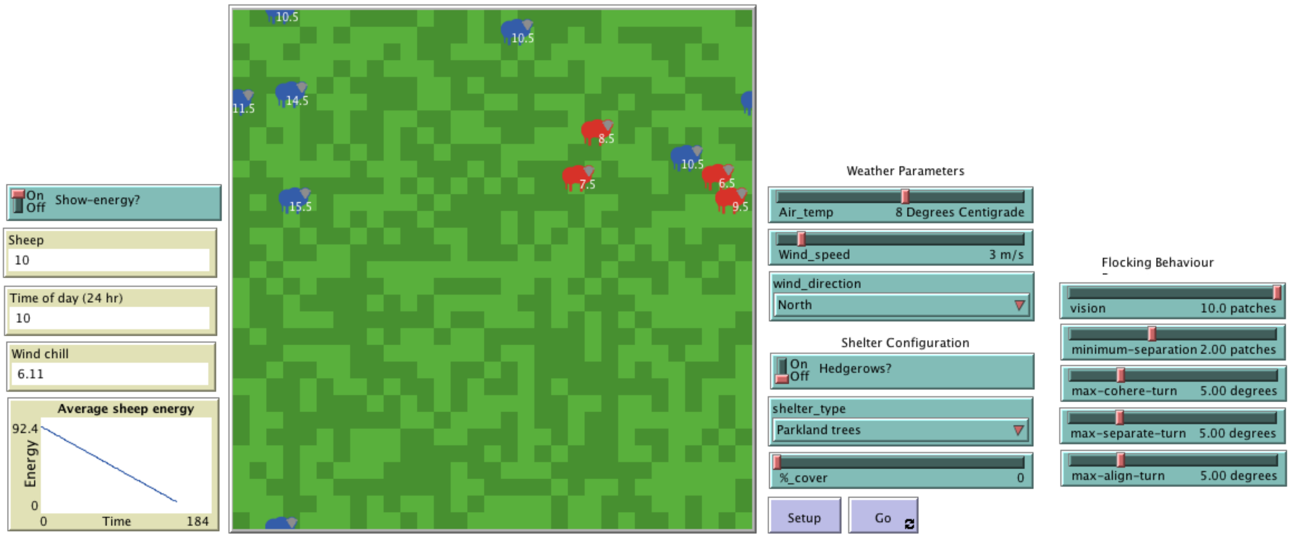
Figure 5. Shelter ratio (reduction in wind speed from ambient weather station normalised to a value of 1) for south easterly wind direction, with artificial and natural shelter visible in the test field.

Table 7. Spatial correlation of slope and windspeed with z-scores outputs from hotspot (Getis-Ord Gi*) analysis for the prevailing wind direction (SE).

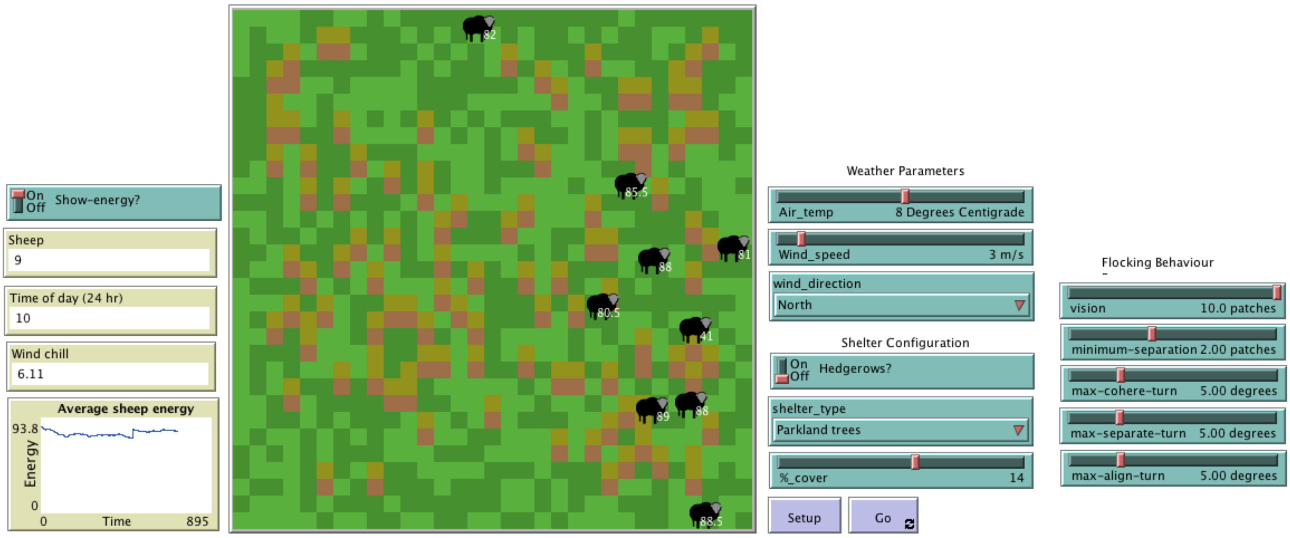
Explanatory variable	Test statistic	Correlation coefficient (r)	95% CI	d.f.	p value
Wind speed	55.913	0.2139	0.2065 - 0.2212	65180	< 0.01
Slope	13.793	0.0539	0.0462 - 0.0615	65180	< 0.01

3.5. Agent Based Model

The Net Logo model illustrates the potential effect of cold stress on livestock energy balance and the benefits offered by hedgerow or tree shelter provision configurable from the interface When sheep agents are in exposed areas of the field, in wind-chill conditions outside of their TCZ, they become cold stressed and seek shelter on the leeward side of the hedgerows or trees. Sheep energy increases when sheep experience temperatures above the TCZ, and decrements when temperature is below the TNZ. Flock health can be monitored using a line graph of average sheep agent health. In wind-chill conditions below the TCZ energy decreases, after finding shelter energy can be seen to increase due to the increase in wind-chill temperature. The benefits of shelter provision can be demonstrated by employing the same weather parameters in different scenarios, for example applying a temperature of 8°C and wind speed of 3 m/s, when run with and without parkland tree cover of 14% results in cold stress and colouring of the agents blue and red (Figure 6).



(A)



(B)

Figure 6. Net Logo model demonstrating shelter seeking behaviour in sheep. (A) Harsh conditions used to illustrate the moderately (blue) and severely cold stressed (red) individuals in exposed areas of the field (B) The beneficial effect of shelter provision in the same weather conditions as (A), through establishment of parkland trees (brown patches), illustrated by the average sheep energy counter.

4. Discussion

Investigation of spatial correlation of ewe position according to calculated localised windspeeds, at 1m spatial resolution, suggests that microclimate is a major factor in influencing sheep behaviour. This is due to the doubling in Moran's *I* when the localised wind speed was used instead of field-scale wind speed, which indicates that spatial clustering increases when the topographical features of the field site were accounted for by the wind field model. Indeed, if the ewes were acting independently of the shelter provided by the artificial and natural shelter features, one would expect to see no effect of integrating localised wind speeds.

Statistical analysis of preference indices revealed that ewes had a preference for the areas of natural and artificial shelter, which supports the established preference for these areas [3]. Whilst a significant difference was not recorded between two of the artificial shelters (2 & 3) and the exposed area, analysis at 2.H of the shelter, where one would predict the greatest sheltering effect, still reveals a higher preference for these shelters. When considering the weather conditions experienced throughout study period, the mean temperature of 6.18°C ± 2.91 (Table 1) lies outside of the zone of thermal comfort for adult ewes [28], and the average wind speed (3.73 m/s or 13.43 km/hr) exceeds the 8 km/hr threshold of sheltering behaviour for lambing ewes [38]. Consequently, the ewes were often experiencing cold stress, creating the conditions where one could expect to see shelter-seeking behaviour occurring. These environmental parameters, in addition to the preference for sheltered areas, suggests that sheltering behaviour is being exhibited by the ewes.

Furthermore, the preferred sheltered areas are also spatially linked to the significant cold spots, identified during hotspot analysis, for both temperature and wind-chill, which surround the natural shelter, shelter 1 and sections of hedgerow. These indicate that the ewes were utilising these areas during spells of colder weather, relative to the conditions within the study period. In reverse, the large area of hotspots for windspeed identified in the northwest portion of the field, again surrounding the artificial shelter and the natural shelter, reflects a greater proportion of moments where the sheep were in this area during high winds. Again, if utilisation of the sheltered areas was occurring irrespective of microclimate, one would not expect the pattern of hot/cold spots indicating occupation of these areas during more adverse weather conditions.

Consequently, when considering the ewe preference for sheltered areas, alongside the presence of cold/hotspots in weather variables and the increased clustering according to localised wind effects; this work concludes that shelter-seeking behaviour is being exhibited by the sheep, and that microclimatic factors are a major component in driving this behaviour.

However, it is important to consider other explanations of why the ewes may be clustering in the northwest portion of the field, irrespective of the shelter present there, particularly regarding the lack of utilisation and absence of cold/hotspots overlaying artificial shelters 2 and 3. One such factor, topography, which is known to influence surface wind speed [39], was worthy of investigation due to the presence of a plateau in the north western region of the test site. As such, hypothesis 3 was constructed to specifically test the influence of topography in driving shelter-seeking behaviour. Application of spatial correlation assessment between slope and hotspot z-score value indicates that topography, although significant, is not an important explanatory variable, with a correlation coefficient close-to-zero. In contrast, the spatial correlation between local windspeed ratios and hotspot z-scores reveals local windspeed is correlated with the hotspots, again linking the localised wind dynamics of the site and the utilisation of sheltered areas during periods of high wind. These findings lead to the rejection of hypothesis 3, whereby landscape topography is not driving shelter-seeking behaviour in the ewes.

There are also a small number of contradictory hot/coldspots were scatted throughout the exposed region of the test site, which are of note, such as a coldspot for wind-chill. This is hypothesised to reflect the noise that could be expected within a natural experiment using animal subjects, and could be removed in future studies [40]. The cold and hotspots which are within 10-20m of the natural and artificial shelter are likely to still be within a sheltered zone, as Baker et al. (2015) notes how the wind break effect can persist up to 14 times the height of the shelter. The significant coldspot for both windspeed and temperature on the sparsely treed eastern boundary of the test site could evidence of sheltering from the prevailing south-easterly wind, which would be in accordance with the lone tree sheltering documented in Merino sheep [18]. However, the coldspots may also be anomalous, as the location also contains a gateway to the adjacent field and farm buildings, and closer proximity to anthropogenic influence which could bias the sheep's occupation of that area [22].

Wind-chill, being a combinatory weather variable, presents greater clusters of coldspots surrounding the sheltered areas, when compared to the analysis of temperature in isolation. Moreover, in the investigation of spatial autocorrelation for the explanatory weather variables in this study, wind-chill reported the greatest Moran's *I* and the greatest clustering in sheep location according to high or low wind-chill values. Early research [14] documented how sheltering behaviour was triggered in Scottish Blackface hill sheep when wind speeds exceed 24 mph and at temperatures below freezing, with little effect by other variables such as rain. Consequently, if these earlier studies had calculated wind-chill effect, it seems they would agree that wind-chill is perhaps the most important driver of shelter-seeking behaviour. These findings could illustrate how integration of individual elements of microclimate, such as wind speed and temperature to produce wind-chill, could explain a greater proportion of the microclimate induced variability in sheep behaviour. To test this hypothesis in future studies, further elements of microclimate, like rain, could be integrated into an explanatory variable using measures like the sheep chill index [18].

Whilst this thesis argues for the importance of microclimate in determining sheep behaviour and spatial positioning, it is important to acknowledge how other temporal and spatial factors, such as social interaction, could be influencing sheep position in any one moment [41]. The presence of hotspots for temperature and wind-chill in the exposed region of the field indicates that the sheep occupy this area in warmer weather (during the spring period of this study), during which they may be displaying non-sheltering behaviour, such as grazing [42]. The temporal variability in behaviour was also recognised by the hotspot analysis of the 8 hour stratification of windspeed, where the large cluster of hotspots in the 12pm-8am time window indicates the sheep were positioned near the natural and artificial shelter during high wind speeds. During this coldest period of the day, where the sheep are outside their TCZ, high winds shall result in greater loss of heat [9], which explains why greater clustering around the shelters is being observed. In reverse, less of an effect (smaller clusters of hotspots) was noted throughout the warmer periods of the day, when cold stress is less likely to be a determinant of sheep behaviour.

The Moran's *I* for windspeed for the 12pm-8am time window corresponds to the hotspot analysis, rising from 0.07 for the daily index to 0.2, indicating greater clustering in sheep position according to wind speed in this period, when compared to the remainder of the day. However, this effect was not consistent for wind-chill and temperature, where clustering peaked during daylight hours (8am-4pm). Again, this could reflect non-shelter-seeking behaviours which cause sheep to cluster, such as grazing or socialising [43], which, depending on the weather, may be more likely to occur during the day [42]. These behaviours could potentially skew any microclimate related clustering documented in the Moran's indexes. This consideration illustrates the importance of considering shelter-seeking behaviour within a broader framework of dynamic ethological traits [44].

One such trait, predator avoidance, has been documented in domestic sheep [45], and could be influencing the ewes occupation of the north western portion of the field. As the area presents one of the highest elevation areas, it offers an optimal viewpoint to perceive predators. Furthermore, the sheep could be selecting this area due to the perceived protection from predators offered by the thicker band of gorse, which may represent a vestigial behaviour of predator avoidance-habitat selection that has been noted in non-domestic sheep (*Ovis canadensis)* [23,46]. These influences could act in conjunction with the cold stress drivers of shelter-seeking behaviour, highlighting how microclimate alone is unlikely to be the sole determinant of this behaviour.

In addressing the limitations of this study and suggestions for future research, whilst the number of sheep tracked in the study site was in accordance with similar studies [18] N=10), expanding the number of subjects would increase the certainty of any documented behaviours being representative of the wider population. This principle also applies to the temporal scope of the study, whereby extending the time period to include more extreme weather conditions would enable more robust conclusions regarding sheep responses to microclimate, as argued by Pollard and Littlejohn (1999). One could predict that the shelter-seeking behaviour exhibited in this study could become more pronounced during winter conditions [14], which could offer potential for further research in this field. Finally, future studies could place greater emphasis on utilisation of the leeward side of shelter, by further stratifying the data according to the wind direction, which would examine sheltering behaviour in finer resolution.

The continued usage of on animal sensors to investigate shelter-seeking behaviours also holds promise for future research. For example, GPS collars are advantageous in monitoring behaviour they are able to recorded location for 24 hours a day, as a posed to the during daylight hours when using visual observations [3]. Furthermore, the integration of skin temperature or posture alteration sensors with the computational approach to calculate localised wind speeds, demonstrated in this study, could provide fine resolution data on microclimate related sheep experience and condition [25]. When combined with GPS technology, these data may be able to provide high resolution, breed-specific behavioural temperature thresholds for livestock species, which will be critical to understand the efficacy of productivity enhancement through silvopastoral interventions [26].

Given the inherently practical nature of the agroforestry research, this work aims to provide useful information to land-owners and practitioners working on silvopastoral systems. For example, the iterative framework used to study the Innovis upland sheep farm could provide a useful structure for informing decisions regarding silvopastoral intervention. By first establishing the productivity enhancing effect of the intervention [3], then exploring the underlying drivers of the behaviour/dynamic, the research has provided evidence to practitioners which can inform choice in silvopastoral intervention. This evidence based approach shall be critical to accompany the likely increase in the application of agroforestry [8].

With regard to the efficacy of the shelter designs in providing effective protection, the drop in time spent (PI) by shelters 2 and 3 at 5H indicates that when sheep remained close to the tyre wall when they were sheltering. The greater concave shape of shelter 1 may have provided greater quality shelter when compared to shelters 2 and 3, which is supported by the favouring of shelter 1 at both 2.5H and 5H parameterisations. This finding contradicts other research [22], which found a preference for an cross "X" shaped design, however, it could be that this may reflect the microclimate dynamics of the site, rather than the shelter design per se.

The greatest preference for any area in test field was for the natural shelter, which indicates that the gorse and ditch in combination offered the best protection to the sheep. This finding is supported by the computed wind field ratios, which documented the greatest sheltering effect (greater area with lowest wind speed ratio) by the gorse and hedgerows (Figure 5). However, when applying the wind field model, it should be noted that the visual lumpiness of the shelter effect is likely to be an artefact of the point sampling used in its construction. Furthermore, the sheltering effect of some hedgerows may be reduced due to a lack of sample points, or large values of height normalised distance for any sample points. Whilst this work documented a preference for natural shelter, the variety of shelter types that are deemed suitable, as reviewed by Pollard (2006), suggests that both artificial and natural shelter types can be effective, albeit without any carbon sequestration capability [47] and biodiversity benefits [4] in the former.

As the results of this study are in accordance with previously established cold stress temperature thresholds, the Net Logo model employed these parameters to trigger shelter-seeking behaviour in the agents/sheep. Whilst the ABM model is still in its first incarnation, the principle of modelling cold stress in sheep to assess the utility of silvopastoral interventions could be a useful tool for land-owners and practitioners. With this application in mind, possible expansion on the model could include: altering the temperature thresholds to specific breeds, integrating empirical evidence on the productivity loss associated with cold stress, choosing tree planting designs to represent orchards/forestry operations, including grazing behaviour with sheep metabolism, including fodder from hedgerows for livestock and the effects of sheep density on pasture degradation with or without trees.

5. Conclusions

This work examined the microclimatic drivers of shelter-seeking behaviour in sheep, specifically investigating the influence of wind-speed, wind-chill and temperature. The statistically significant difference in the occupancy of sheltered areas, compared to exposed areas, indicates sheltering is occurring. Furthermore, the significant coldspots and hotspots for wind-chill, temperature and windspeed respectively, illustrate how sheep were clustering around sheltered areas during cold periods with high wind. Finally, the effect of integration of local windspeed to double the Moran's *I* value, indicates greater spatial clustering according to topographical wind effects of the site. Considering these 3 lines of evidence, this work argues that shelter-seeking behaviour is being observed in both artificial and natural shelter types, thereby accepting the first hypothesis. Moreover, wind speed, temperature and wind-chill are revealed to be key components driving this behaviour, accepting the second hypothesis, with localised wind speed and wind-chill explaining the greatest variability in sheep position. Alternate behaviours influencing the ewe's location in any moment may include grazing, socialising and predator avoidance. The topography of the field, whilst significant, was not an important explanatory variable of sheltering behaviour, therefore rejecting the third hypothesis posed in this study. Further application of GNSS technology to investigate sheltering behaviour, over longer time periods and in more adverse weather conditions, shall better develop our understanding shelter-seeking behaviour in sheep and advance the ABM produced in this work, which holds promise as a tool to inform silvopastoral interventions in the future.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

Author Contributions: Conceptualization, A.S., P.W, P.D., C.P., J.A-W., S.H. and D.J.; methodology, J.A-W., S.H. and C.P.; formal analysis, J.A-W. and S.H.; visualization, S.H. and J.A-W.; supervision, A.S., P.W., P.D., D.J. ; Writing – Review & Editing, J.A-W., S.H., A.S. P.W., P.D., C.P.; project administration, A.S., P.W., D.J.; funding acquisition, A.S., P.W., P.D., D.J., J. A-W. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by a Knowledge Economy Skills Scholarship (KESS 2) in collaboration with Innovis Ltd. and the Woodland Trust. KESS 2 is a pan-Wales higher level skills initiative led by Bangor University on behalf of the Higher Education sector in Wales. It is part-funded by the Welsh Government's European Social Fund convergence programme for West Wales and the Valleys, grant number 80815. Further funding was provided by the Santander University Employability Scheme.

Data Availability Statement: "Not applicable".

Acknowledgments: The authors would like to thank the shepherding staff at the study farm for enabling this trial to be conducted on their breeding flock; without their collaboration this project would not have been possible.

Conflicts of Interest: The authors declare no conflict of interest and the funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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