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Report on development of meta-models on the effect of climate parameters on animal productivity and welfare

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Table 1 – Key information

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Abstract

Projected climatic changes in Europe will affect small ruminant systems through direct effects on animal performance (e.g. heat stress), and indirect effects on pasture and forage availability. The purpose of the task 3.3 is to develop meta-models that could capture these effects at the animal level. In conjunction with task 3.2, which focus on pasture production, these meta-models will be incorporated in the whole-farm model to be developed in WP4, aiming to capture the subsequent consequences of climate change for small ruminant systems.

While environmental factors can influence many different aspects of the animal performance, the task 3.3 focus on analysing the potential impacts of thermal stress on animal production and health/welfare, due to its particular importance within the farm system (which represent the boundaries of this task, leaving out others aspects like transport). In the first section of this document, two meta-modelling approaches for assessing the effects of heat stress on the productivity of small ruminants are described, based on the application of the temperature-humidity index (THI) as an indicator of heat stress intensity. The first one is a semi-mechanistic meta-model, which aims to consider the effects of heat stress on the animal's energy balance: mainly through a decrease in feed intake and an increase of maintenance requirements. In the second approach, an empirical procedure is followed based on merging production data records with weather information, in order to extract potential relationships under heat stress conditions. Strengths and limitations of both approaches are analysed, with particular attention to its implementation within the whole farm model of WP4.

In the second section of the document, a heat comfort index is developed so animal welfare aspects related to heat stress could be assessed qualitatively in the modelling framework developed in WP4 ($SIMS_{SR}$), at least for comparison purposes. The index is based on identifying the different stages of diminished welfare due to heat stress in small ruminants, and assigning them different scores. In addition, the index aims to capture the potential effect on welfare status of several strategies to alleviate heat stress in farm animals (e.g. shelters, shade, ventilation, sprinkles) through expected changes in the HS thresholds. Finally, the main diseases and health issues affecting small ruminant systems whose incidence or distribution may be affected by climate change are identified. As capturing the variety of potential risk effects through a single meta-model was not feasible, the main modelling approaches described in literature for predicting animal disease evolution linked to

changes on environmental conditions are provided so they could be implemented into the modelling framework for more specific analysis.

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1 Introduction

Projected climatic changes in Europe will affect small ruminant systems through direct effects on animal performance (e.g. heat stress), and indirect effects on pasture and/or forage availability (e.g. changes in quantity and/or quality). As a first step to explore the potential implications that these changes could have for small ruminant production and how the sector could react to them, a review was conducted (Task 3.1) of the best-to-date information available on interactions between climate and sheep and goat systems. The literature identified and the data extracted from this review has been used and processed as a basis for developing and validating of semi-mechanistic meta-models that help to relate the effect of weather and site conditions on sheep and goat performance (Task 3.3). In conjunction with Task 3.2, which focus on pasture production, these meta-models will be incorporated in the whole-farm model to be developed in WP4, aiming to capture the subsequent consequences of CC for small ruminant systems, and assist with the identification of appropriate innovative solutions in WP5.

Therefore, the present task is specifically focus on developing meta-models that could capture the effects of climate change at the animal level. While environmental factors can influence many different aspects of the animal performance, this task focus on analysing the potential impacts of thermal stress on animal production and health/welfare, within the boundaries of the farm system.

2 Effects of thermal stress on animal productivity

Sheep and goats are homeothermic species, which means that they aim to maintain a balance between heat of metabolism and heat of environment. Environmental conditions, such as temperature, humidity and solar radiation, may affect substantially their thermoregulation capabilities. Within the limits of their thermoneutral zone (TNZ) minimum effort is required to keep constant body temperature, animals are comfortable and greatest production performance (e.g milk yield, growth rate) is achieved. However, when exposed to extreme environmental conditions above or below the TNZ, different physiological and behavioural responses are triggered in an attempt to adapt to the thermal stress.

The general responses to heat stress (HS) in sheep and goats often include raised respiration rate, heart rate and rectal temperature, panting, drooling, sweating, increased drinking and reduction of feed intake. Changes in their metabolisms of water and energy, enzymatic reactions and hormonal secretions are also induced (Marai et al., 2007). All these mechanisms involve an additional consumption of energy and often results in impairment of productivity rates, however not all of them are triggered immediately or at the same level, as it will depend very much on the intensity and duration of the heat stress suffered (Figure 1).

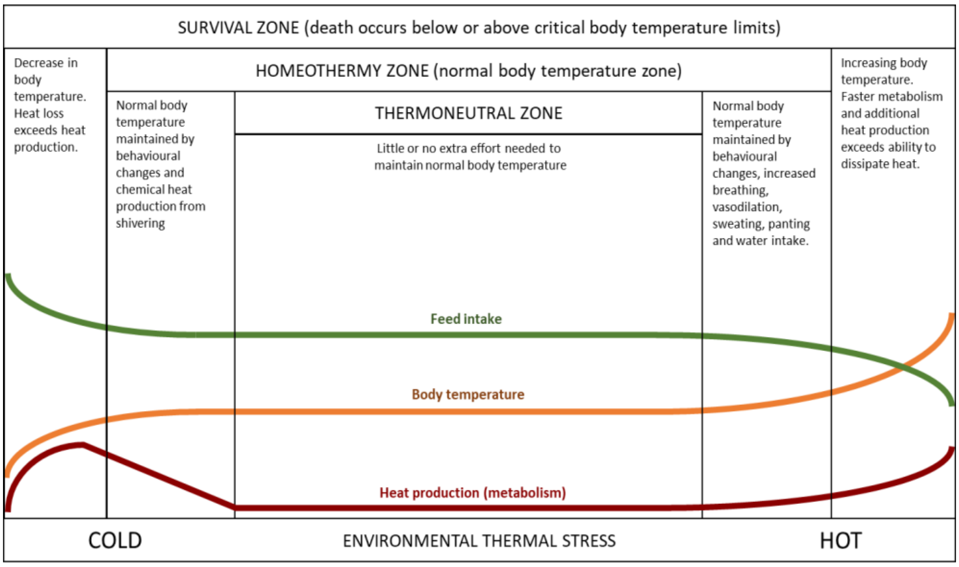

Figure 1. Different levels of response to thermal stress in small ruminants. (Adapted from Silanikove 2000 and NRC 1981).

As explained previously, measuring the heat load exposure of an animal using air temperature can be misleading though. For that reason, the thermal stress severity in animals is often estimated by the temperature-humidity index (THI), which accounts for the combined effects of ambient temperature and relative humidity. According to Kelly and Bond formula (1971), THI calculation is:

$$THI = (Tdb(ºF) - ((0.55 - 0.55 \cdot RH) \cdot (Tdb(ºF) - 58) \qquad (1)$$

where Tdb is the dry bulb temperature in ºF and RH is the relative humidity. When the temperature is expressed in ºC, the previous equation changes as follows (Finocchiaro et al., 2005)):

$$THI = (Tdb(ºC) - ((0.55 - 0.55 \cdot RH) \cdot (Tdb(ºC) - 14.4) \qquad (2)$$

Based on the application of THI as an indicator of heat stress intensity, in the current task, two different approaches to assess the effects on productivity of small ruminants have been studied. In the first one, a semi-mechanistic approach is proposed, which aims to consider the potential effects of heat stress on the animal's energy balance. In the second one, an empirical procedure is followed based on merging production data records with weather information, in order to analyse potential relationships. In a last section, strengths and limitations of both approaches are analysed, with particular attention to its implementation within the whole farm model of WP4.

2.1 Thresholds of heat stress

In general, sheep and goats seem to be less susceptible to environmental stress than other domesticated ruminant species (Lu, 1989). The literature on heat stress describes thermoneutral zone for sheep between 12ºC and 25ºC (Bianca et al., 1970; Curtis, 1983; Taylor 1992; Nikitchenko et al., 1988; Mishra, 2009). A higher heat stress threshold can be expected for goats, as they tend to tolerate heat better than sheep, because of different adaptation mechanisms (i.e. anatomical, morphological, physiological, metabolism) especially well-suited to hot and/or dry conditions (Al-Dawood et al., 2017; Robertshaw and Dmi'el, 1983). Appleman and Delouche (1958) suggested that the limit of heat tolerance for goats could lie between 35ºC and 40ºC, although they observed initial signals of heat stress when goats were exposed to 30ºC. Similar values for heat stress threshold on goats have been reported by other authors, indicating a range among 28-30ºC (Salem et al., 1982; Shkolnik et al., 1972; Lu et al., 1989).

According to the studies mentioned and the heat stress levels described in literature, THI thresholds for sheep and goats under HS are proposed, so they can be applied through this work (Table 2). For sheep, the ranges indicated by Marai et al 2007 are applied (THI<22.2=absence of heat stress; 22.2 to <23.3 = mild heat stress; 23.3 to <25.6 = moderate heat stress; >25.6 severe heat stress), as they are in accordance with the temperature threshold for HS on sheep around 25ºC (THI=22.1 assuming 50%RH) reported by a number of studies (Bianca et al., 1970; Curtis, 1983; Taylor 1992; Nikitchenko et al., 1988; Mishra, 2009).

For goats, the same ranges among HS levels were maintained but considering 28ºC as the temperature threshold at which HS conditions starts (THI=24.3 assuming 50%RH) (Appleman and Delouche, 1958; Salem et al., 1982; Shkolnik et al., 1972; Lu et al., 1989). This approach leads to a limit of heat tolerance (i.e. extreme-severe HS stress conditions) for goats around THI=31.4, which is in accordance with reviewed studies suggesting it could range among 35-40ºC (THI=30.1-33.0 assuming 50%RH) (Appleman and Delouche, 1958).

Table 2. Thresholds for different heat stress levels in sheep and goats.

	SHEEP	GOATS
Heat stress class	**THI range**	**THI range**
Thermoneutral	<22.2	<24.3
Mild stress	22.2 – 23.3	24.3 - 25.4
Moderate stress	23.3 – 25.6	25.4 – 27.7
Severe stress	25.6 – 29.3	27.7 – 31.4
Extreme-severe stress	>29.3	>31.4

Applying specific TNZs in the meta-model may involve an important limitation, especially considering the diversity of breeds and systems in the small ruminants' sector, and the many factors affecting HS conditions, such as the breed, animal stage, productivity level or HS alleviation measures in the farm. Specific approaches were incorporated into the meta-model to capture the influence of some of this factors, at least for comparison purposes (described in section 3.1 below), by increasing or decreasing THI_{HS} thresholds depending on the case. Assuming the limitations of the TNZs proposed here, they are applied through the description of the semi-mechanistic meta-model (approach 1) in the sections below, in order to show its potential capabilities and as a first attempt to validate it against experimental data from reviewed studies.

2.2 Approach 1: Semi-mechanistic meta-modelling

Decreased productivity under heat stress (HS) conditions has traditionally been attributed to the feed intake reduction usually observed in animals exposed to a high thermal load. However, recent studies have pointed out that feed intake and production can sometimes have dissimilar responses to HS, indicating that both, direct and indirect (feed intake) mechanisms could be involved in the productivity reduction associated to HS (Baumgard and Rhoads et al., 2012; Mahjoubi et al., 2014).

As described in the previous section, when animals are exposed to environmental conditions out of their TNZ, different physiological and behavioural mechanisms are triggered. These responses ultimately involve relevant consequences for their energy balance.

For example, an increase in energy consumption is required to maintain the different heat dissipation methods activated by the animals to combat hot environments (e.g. sweating, panting, increased respiration rate). In addition, feed intake is often reduced under heat stress in order to reduce heat production and feed transit through the digestive tract (Sevi et al 2012; Marai et al 2007).

As a result, the dietary energy and the energy efficiency of the animal are significantly altered, which may induce a decline on productivity in terms of growth rate or milk yield (quantity and/or fat and protein contents) (Abdalla et al., 1993).

The partitioning of feed energy within animals is described schematically in Figure 2 (adapted from NRC 1981). Intake energy (IE) is the energy ingested per day, and is determined from the feed voluntary intake and the energy density of the feed. As feed is not completely absorbed by the organisms, digestible energy (DE) represent the available portion of IE once energy loss through the faeces is accounted. Metabolizable energy (ME) is the energy remaining after faecal, gases and urinary energy losses, and represents the energy available for productive functions, such as growth or reproduction, and for supporting metabolic processes (i.e. maintenance) of an animal, such as activity for obtaining nutrients, respiration or thermoregulation mechanisms.

In this approach, the energy balance is used as the basis to capture the potential consequences that heat stress may have on productivity by considering within the meta-model the direct effects on two main aspects: the energy requirements for maintenance and the decrease in feed intake.

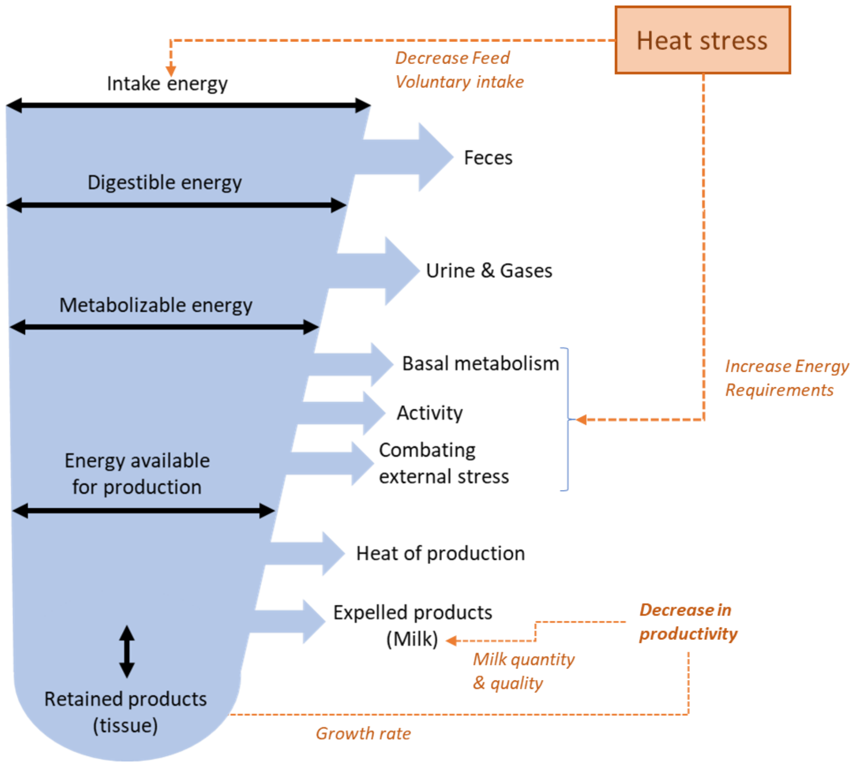

Figure 2. Partition of feed energy within the animal and potential effects of heat stress on the energy balance (Adapted from NRC 1981).

2.2.1 Energy requirements for maintenance

Under heat stress conditions energy requirements for maintenance are expected to be significantly increased (by 7-30% (NRC, 2001)) mainly due to a rise in body temperature and respiration rate (Sevi et al., 2012). Unfortunately, limited studies have reported estimations about the energy needs for small ruminants during heat exposure.

The magnitude of the increase in energy requirements will depend on the severity of heat stress, which can be related to the increased energy cost of panting, among other factors. Therefore, the type and intensity of panting has been proposed as a proxy to estimate the level of heat stress (NRC, 1981; Silanikove 2000). When the animal is in the first stages of heat stress, modest panting (i.e. rapid shallow panting) is usually identified. An increase about 7% in the maintenance requirements has been estimated during this phase. In contrast, severe heat stress conditions are associated with deep open-mouth panting, which may increase maintenance requirements between 11-25% (NRC, 1981).

The cooling mechanisms of the animal are intensified exponentially with the external hot conditions and body temperature (Silanikove 2000), although other physiological and behavioural responses are also triggered that may partially counteract this effect. For example, under severe heat stress conditions, a reduction in feed intake is usually induced, which involves a decline of the metabolic heat production, thus decreasing the internal heat load in the animal. Nevertheless, in contrast to cold exposure, non-linear increase of energy demands during hot conditions has been suggested (Graham et al., 1959; Ames et al., 1971). This has mainly been attributed to the effect of temperature in the rate of physiological processes, and the decline in the efficiency of evaporative mechanisms. During the transition from rapid shallow painting stage (moderate heat stress) to slower deeper breathing of severe heat stress a decrease in the thermoregulatory efficiency of sheep have been observed (Hales and Brown, 1974, Hofman et al., 1977)

Based on the considerations described above, we aimed to develop an equation to adjust the proportional increase in energy requirements for maintenance according to the environmental factors (i.e. temperature, humidity) related to heat stress level suffered. To do so, the THI thresholds indicated by Marai et al., 2007 for small ruminants (THI<22.2=absence of heat stress; 22.2 to <23.3 = mild heat stress; 23.3 to <25.6 = moderate heat stress; >25.6 severe heat stress) were used as a proxy of the subsequent thresholds for HS strages, which were related to the energy requirement estimations described from NRC 1981, 2001 (Table 3).

As a result, an exponential relationship was developed relating the proportional increase in energy requirements according to the environmental conditions (i.e. THI), as a proxy of the heat stress level suffered (Figure 3). Based on this relationship, the equation is finally adjusted to the correspondent THI_{HS} threshold for sheep (THI_{HS}=22.2) and goats (THI_{HS}=24.3) respectively.

Table 3. Relationship established among heat stress level, increases estimated for maintenance energy requirements (NRC, 1981, 2001) and THI thresholds for small ruminants proposed by Marai et al., 2007.

Heat Stress level	Energy requirement increase (based on NRC, 1981, 2001)	THI thresholds for small ruminants (based on Marai et al., 2007)
Mild HS	0-7%	22.2-23.3
Moderate HS	7-11%	23.3-25.6
Severe HS	11-25%	25.6-30.0
Extreme HS	>25%	>30.0

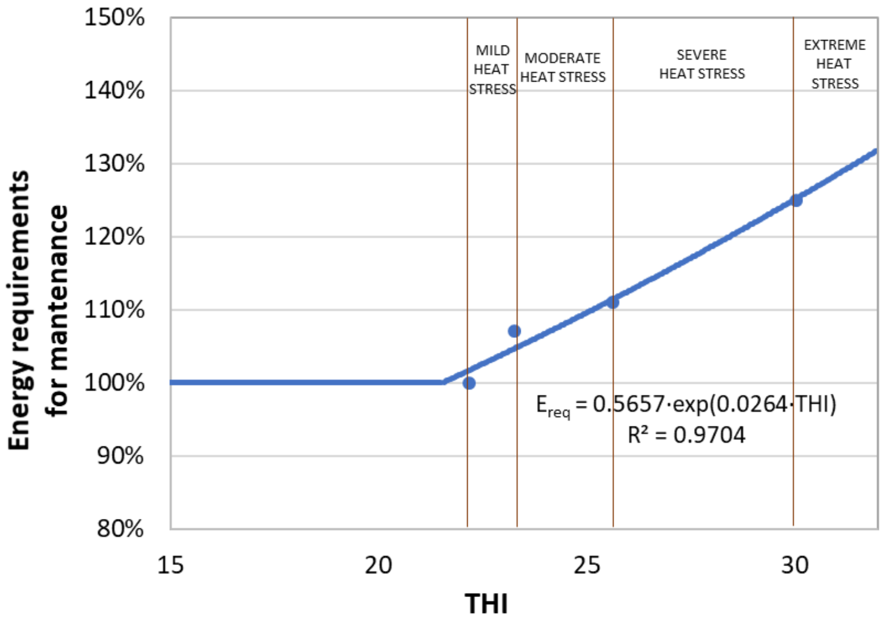

Figure 3. Equation developed to estimate the additional energy requirements for maintenance according to environmental conditions (THI), related to different HS levels (Adapted from NRC 1981, 2001).

When animals are exposed to cold stress conditions (below TNZ), different mechanisms to compensate for increased energy loss because of higher temperature gradient are activated. The specific details of these responses to cold environmental conditions, as well as the precise thresholds for cold stress for small ruminants are beyond the scope of this task, but existent approaches for estimating the implications in terms of energy requirements have been analysed, so it can be incorporated into this meta-model.

Two main factors determining the rate of heat loss, (and consequently the change in energy requirements for maintenance) can be pointed out in small ruminants under cold stress: a) the thermal gradient between body core temperature and external ambient temperature, and b) the insulation provided by the tissue, wool or hair of the animal.

Based on these two factors, the following linear equation can be used to estimate the effect of cold conditions on the maintenance energy requirements of small ruminants (based on NRC, 1981):

$$E_m = a \cdot BW^{0.75} + b \cdot AT / I \qquad (3)$$

Where ME_m (MJ/day) is the metabolizable energy for maintenance corrected for effective temperature, BW (kg) is the body weight of the animal, AT (ºC) is the thermal gradient between animal's cold stress temperature threshold and ambient temperature, I (ºC/MJ/m^2/day) represents the total insulation provided by the hair or wool, a (MJ/day/kg) is the coefficient of energy maintenance requirement for a specific animal under no thermal stress and b (m^2) is the body surface area of the animal.

Coefficients for calculating energy for maintenance can be obtained from different guidelines for nutrient and energy requirements (e.g. 0.217 MJ/day/kg for sheep, 0.236 MJ/day/kg for lambs to 1 year) (AFRC, 1993). For estimating body surface area, the equation proposed by Bennett (1973) can be applied:

$$b = 0.094 \cdot BW^{0.67} \qquad (4)$$

According to Blaxter et al., (1959) wool insulation capacity is about 0.007 ºC/kcal/m2/day per cm depth. Total insulation can be inferred from that coefficient and the estimated fleece depth. As a result, insulation provided depending on fleece depth can have a significant effect on the energy requirements for maintenance under cold stress conditions, as can be seen in Figure 4.

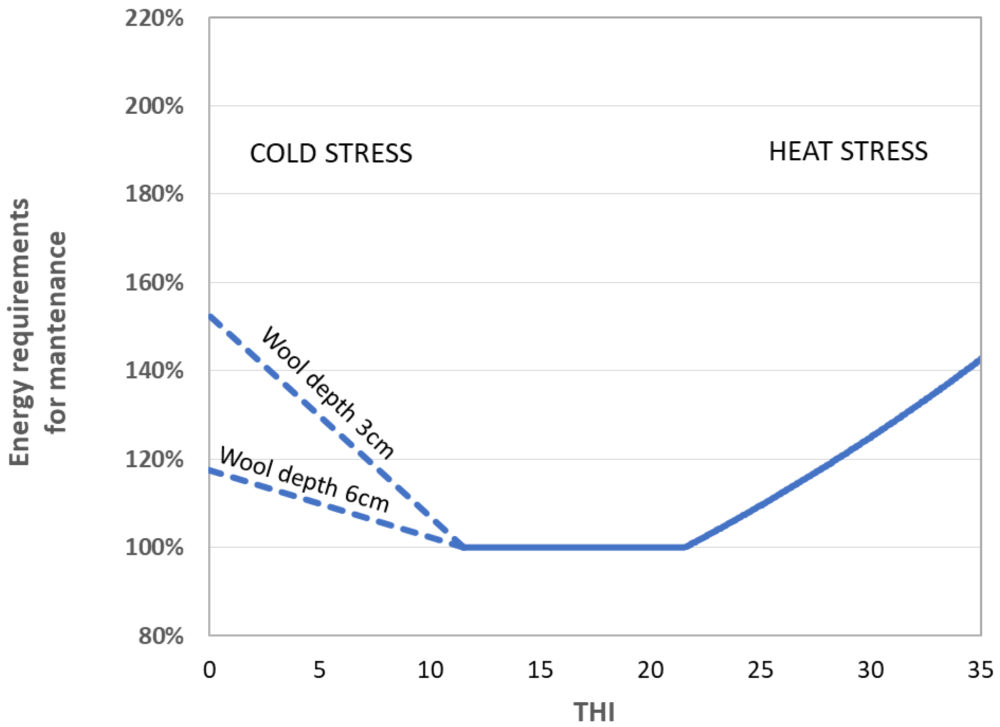

Figure 4. Estimation of increase on energy requirements for maintenance under cold stress for sheep (assuming THI_{CS} threshold = 11.5 (T=11ºC, RH=50%)) and heat stress conditions (THI_{HS} threshold = 22.2 (based on Marai et al., 2007)).

.2.2.1.1 Validation

Unfortunately, limited studies have reported estimations about the change in energy requirements for ruminants, and particularly for small ruminants, during heat exposure. The results reported in the only study found (Mahjoubi et al., 2014), were used to validate the relationship developed among environmental conditions (THI) and the increase in energy requirements (Figure 3), assuming the THI thresholds proposed by Marai et al., 2007.

The energy increase estimated through extrapolation of the proposed equation (57%) seem in accordance with the values obtained in the study from Mahjoubi et al., 2014 (Figure 5); which suggested an increase by about 66% of energy maintenance costs in growing sheep at THI 38.6, although it could suggest a more important non-linear response under extreme HS conditions (THI>30).

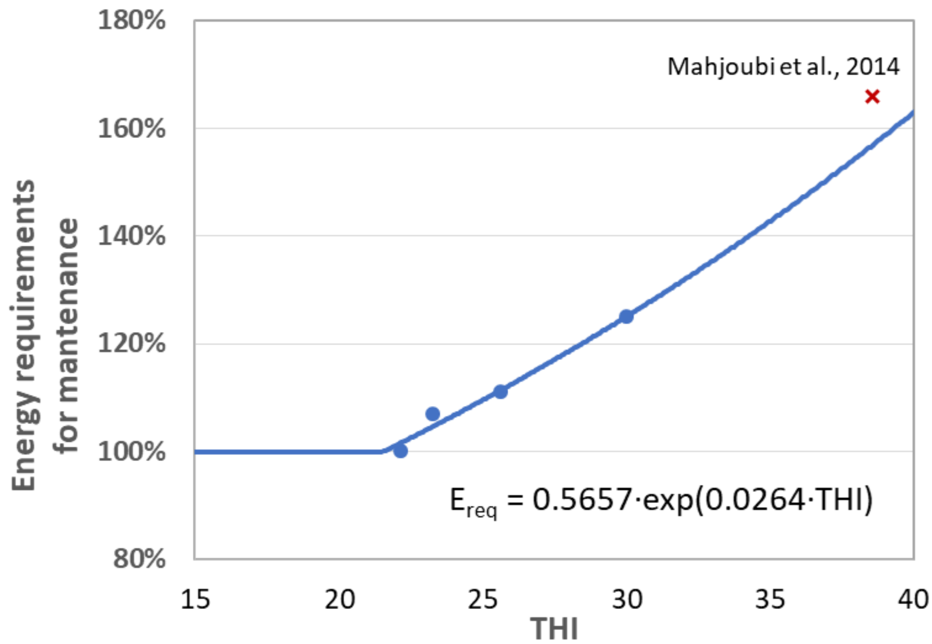

Figure 5. Validation of equation developed relating increase on energy requirements for maintenance with environmental conditions (THI) under HS. Estimated result under extreme HS conditions of THI=38.6 obtained through extrapolation (57%) are in accordance with reported value (66%) by Mahjoubi et al., 2014.

2.2.2 Feed intake

Heat-stressed animals decrease feed intake in an attempt to create less metabolic heat, since the heat increment of feeding is a source of heat production of significant importance in ruminant animals (Kadzere et al., 2002). A number of studies have shown dry matter intake (DMI) to decrease in ruminants under exposure to heat stress, although values for prediction of the interactions among temperature and feed intake for sheep and goats are limited.

The effect of environmental conditions on feed intake was captured following the indications of previous studies (NRC, 1981), suggesting the decline in feed intake for small ruminants under heat stress can follow a similar trend than cows, with a distinction between lactating (dairy systems) and fattening animals (meat systems).

The relationship among feed intake (%) and temperature (ºC) was extracted directly from NRC, 1981 figures for dairy and fattening cattle by using the tool WebPlotDigitizer 4.2 (Rohatgi, 2019) and converting temperature values into THI, assuming 50% relative humidity.

As, comparatively speaking, small ruminants tend to be more tolerant to climatic extremes than other livestock animals (NRC, 1981, Silanikove, 2000, West, 2003), the thermoneutral zone (TNZ) for cattle was modified accordingly to be adapted for small ruminants. To do so, the TNZ for cattle (11-20ºC) extracted from figures in NRC, 1981 was extended in the hot range so it coincided with the THI_{HS} threshold for sheep (THI_{HS}=22.2) and goats (THI_{HS}=24.3) according to the ranges proposed in the previous section based on Marai et al., 2007 (Figure 6 and 7).

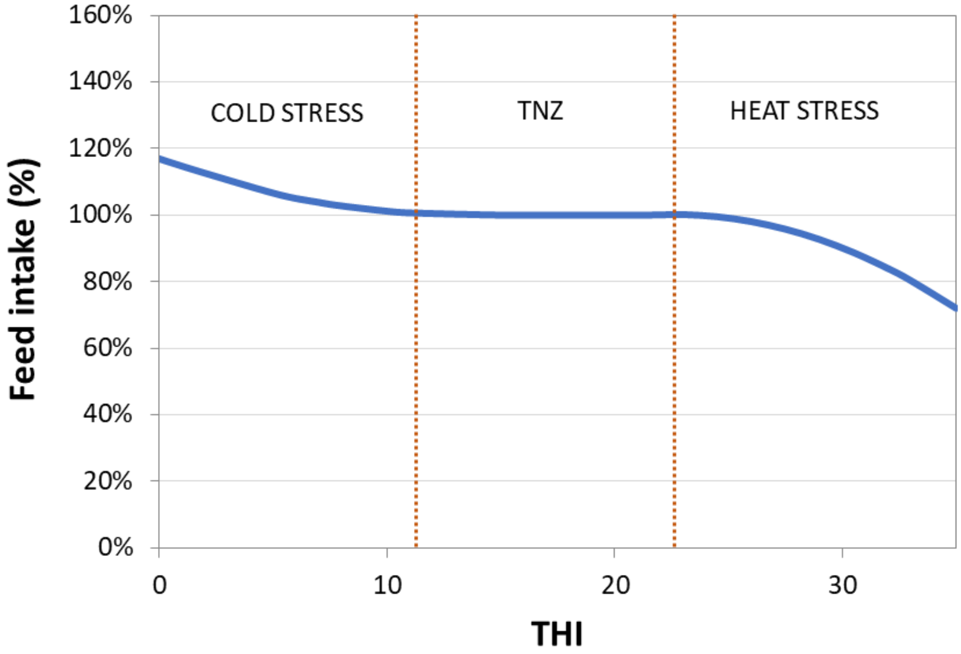

Figure 6. Effect of thermal stress conditions (THI) on feed intake of dairy sheep. (THI_{CS} threshold = 11.5; THI_{HS} threshold = 22.2)

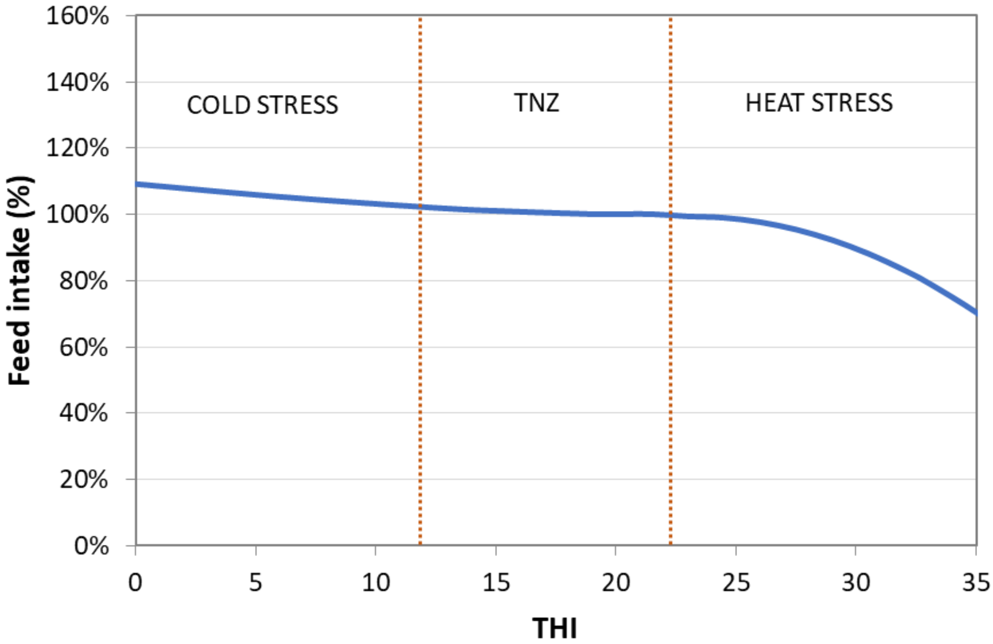

Figure 7. Effect of thermal stress conditions (THI) on feed intake of growing/fattening sheep (THI_{CS} threshold = 11.5; THI_{HS} threshold = 22.2).

.2.2.2.1 Validation

A specific review of the available literature about this topic has been conducted and the collected data has been processed so they could be used to validate this aspect of the meta-model when enough details of the trials were provided. Details of the studies reviewed can be check in Tables A1 and A2 of Appendix.

Therefore, the capability of the proposed meta-model for the estimation of the % feed intake decrease was validated by comparing the estimated values with the experimental measurements published in literature for dairy and meat systems (Figures 8-9). Model predictions of decline on feed intake for dairy systems agreed reasonably well with measured data (Figure 8) as reflected by the high determination coefficient (r^2=0.83). According to the analysed data, the slope value (0.64) may indicate that the model tend to understimate the decrease on feed intake under harsh conditions (in particular for highly productive animals under severe heat stress).

The model also seems to predicts aceptably the feed intake decline in meat systems (slope=0.82, r2=0.46) although higher discrepancies have been observed in this case (Figure 9). Again it appears it may under-predict slightly the decline on feed intake in certain conditions, but there are insufficient points at the low end of the range to confirm this trend.

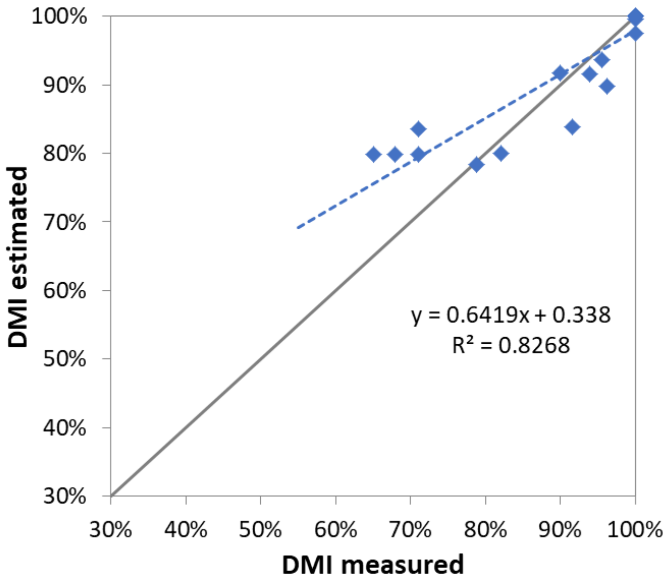

Figure 8. Estimated vs measured reduction of feed intake of dairy sheep and goats under heat stress (Datasets from Abdalla et al., 1993; Bernabucci et al., 2009; Brasil et al., 2000; Brown et al, 1988; Hamzaoui et al., 2013; Hamzaoui et al., 2014; Leibovich et al., 2011; Sano et al., 1985)

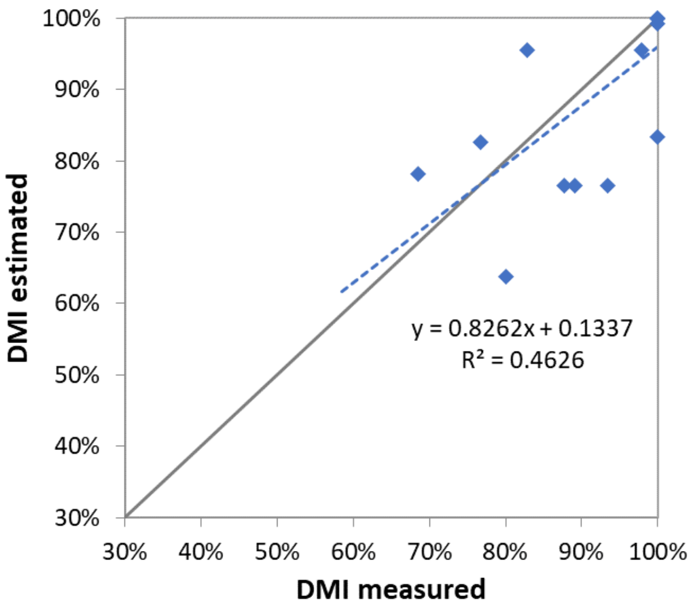

Figure 9. Estimated vs measured reduction of feed intake of meat small ruminants under heat stress (Datasets from Alhidary et al 2012; Bhattacharya et al 1974; Denek et al 2006; Dixon et al 1999; Indu et al 2014; Mahjoubi et al 2014)

2.2.3 Productivity

As described previously, when animals are exposed to moderate-severe heat stress conditions, in addition to cooling mechanisms, other physiological responses are activated aiming to reduce internal heat load. The main one is a reduction of feed intake. Since the efficiency of metabolizable energy (ME) utilization for production is not 100%, the portion of ME that is not retained as new tissue or expelled as a product (e.g. milk) is lost in the form of heat that the animal must dissipate. Thereby, the lower feed intake allows a reduction in thermogenic processes of digestion and metabolic rate, thus decreasing the internal heat load.

When exposure to hot conditions is prolonged in time, additional mechanisms are activated to lower the basal metabolism, such as a decline in the secretion of thermogenic/calorigenic hormones (e.g. growth hormone). If animals are at a productive stage (growth, lactation) these responses to heat stress are accompanied by negative consequences in productivity, due to reduced performance (Silanikove et al., 2000, Renaudeau et al., 2012).

Among the various consequences for animals that heat stress can potentially induce, impaired productivity is a major concern, probably due to its economic implications for producers and processors (Lu, 1989; Marai et al., 2007; Al-Dawood, 2017, and references therein). For example, the decline in milk quantity and quality (%fat, %protein) associated to heat stress is receiving increasing attention, as one of the potential impacts that climate change can have on the future sustainability of small ruminant systems.

A number of studies on dairy sheep and goats have reported decreases on milk production associated to heat stress conditions. However, in many cases, the negative effect of heat stress mainly resulted on a decline on milk quality, usually reflected through a reduction in the total protein content of the milk (Sevi et al., 2001, 2002b; Hamzaoui et al., 2012; Menéndez-Buxadera et al., 2012; Hamzaoui et al., 2013; Ramón et al., 2016). As a proxy to consider the effects of heat stress on milk production and quality together, milk yield was corrected at 6.5 percent fat and 5.8 percent protein (FPCM) according to Pulina, Macciotta and Nuda (2004) using the equation:

$$FPCM\ (kg) = Milk\ production\ (kg) \cdot [0.25 + 0.085 \cdot Fat(\%) + 0.035 \cdot Protein(\%)] \qquad (5)$$

Energy is considered the first limiting factor upon the level of animal production achieved by feeding a specific diet (AFCR, 1993). According to this, as stated previously, the semi-mechanistic meta-model proposed to estimate the decrease on animal productivity under heat stress conditions is based on an energy balance approach:

$$ME_{intake} = ME_{maintenance} + ME_{production} \qquad (6)$$

where ME_{intake} is the metabolisable energy (ME) available through the feed intake, $ME_{maintenance}$ is the metabolisable energy required for fasting metabolism and activity allowance of the animals, and $ME_{production}$ is the metabolisable energy required for growth or milk production.

Under heat stress conditions, a reduction is expected on the ME_{intake} (i.e. feed intake reduction) while an increase is projected on $ME_{maintenance}$ (i.e. energy requirements for cooling mechanisms). As a result, the energy available for growth or milk production ($ME_{production}$) will be reduced, and consequently the productivity, as they are related through these formulas (AFRC, 1993):

$$ME_{production} = EV_{milk} \cdot Y_{milk} \qquad \text{(7a) Lactating animals}$$

$$ME_{production} = EV_{g} \cdot \Delta W \qquad \text{(7b) Growing animals}$$

Where EV_{milk} is the energy value of the milk, Y_{milk} is the milk yield, EV_{g} is the energy value of the liveweight gain of growing animals and ΔW is the liveweight gain. The EVg can be known according to the type of animal and liveweight. Similarly, the EVmilk can be estimated from fat and protein content, and will be fixed assuming a normalised value of FPCM. Consequently, in the proposed meta-model, the effects of heat stress on the energy balance will directly result on an impact on milk productivity (Y_{milk}) or weigth gain (ΔW).

The meta-model was conceptualised in conjunction with Task 4.3, so it can be integrated within the farm modelling framework ($SIMS_{SR}$) developed through WP4 (Figure 10). Besides, all the procedures and methods for estimating energy supply through feed intake and energy requirements for animal's maintenance and production were in accordance with the farm model developed. According to this, the AFRC guidelines (AFRC, 1993) were followed as the reference document.

In $SIMS_{SR}$ a productivity target is set as a starting point. Energy requirements and maximum feed voluntary intake (DMI) values are estimated according to it. Then, energy requirements are sequentially checked to meet demands with ME supply through the diet, accounting for the efficiency of utilisation of ME for each feed and process.

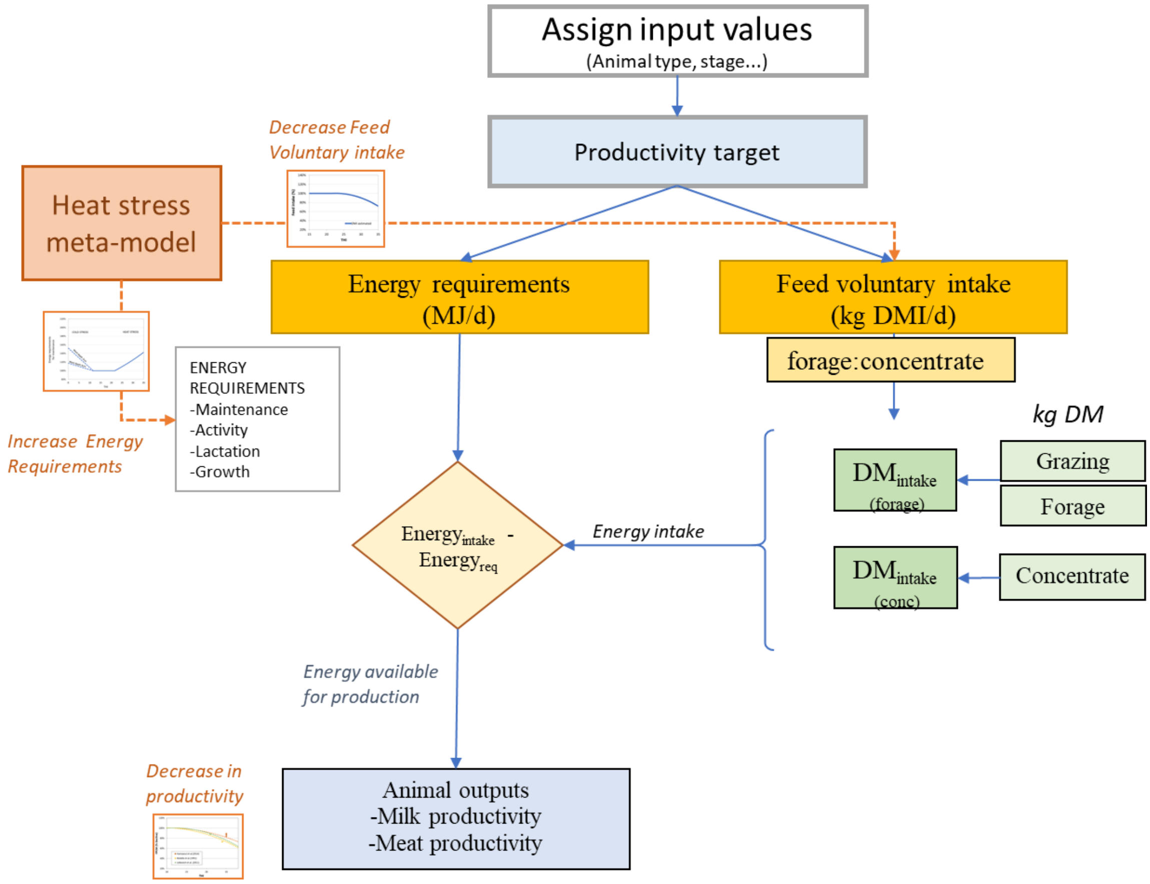

Figure 10. Integration of the heat stress meta-model (approach 1) into the farm modelling framework ($SIMS_{SR}$) to account for potential reduction in productivity.

The meta-model proposed to account animal productivity losses under heat stress conditions will be implemented in $SIMS_{SR}$ by two modules (Figure 10): a) increasing energy maintenance, and b) decreasing maximum feed intake according to the principles and equations described in previous sections.

Moreover, in lactating animals, stress conditions can cause a transient metabolic energy deficit, which will activate an increase in mobilization of energy stored in body reserves. In order to capture this effect, based on AFRC guidelines, a function was developed that relates a gradual mobilization of energy through liveweight loss with heat stress level according to THI:

$$BW_{daily\ loss} = BW \cdot 0.0025 \cdot F_{BW} \qquad (7)$$

where $BW_{daily\ loss}$ is the total liveweight loss (kg/day) in lactating sheep or goats due to heat stress, BW is the liveweight of the animal (which is multiplied by 0.25% to consider a maximum potential

BW loss daily), and F_{BW} is a factor from 0 to 1 that captures a gradual effect of heat stress on body reserves mobilisation (Figure 11).

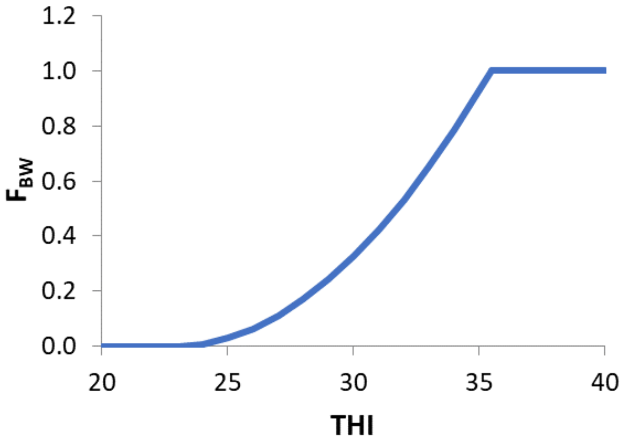

Figure 11. Factor F_{BW} captures a gradual effect of heat stress on BW loss to mobilise reserves on lactating animals under energy deficit.

.2.2.3.1 Validation

A specific review of the available literature about this topic has been conducted through this task and the collected data has been normalised to FPCM and processed so they could be used to validate this aspect of the meta-model proposed when enough details of the trials were described. An overview of the HS studies analysed with their results converted into FCPM is shown in Table A3.

The capability of the proposed heat stress meta-model for the estimation of the decline in milk productivity was checked by comparing the estimated values with experimental measurements reported in literature. Based on the review conducted through this task about heat stress experiments on sheep and goats, those conduced on dairy animals were first filtered. Then, those studies providing details of the feed ingredients and composition, dry matter intake and decline of milk production and composition (%fat, %protein) were selected (Abdalla et al., 1993; Hamzaoui et al., 2014; Leibovich et al., 2011).

The results are shown in Figures 12 and 13. Meta-model estimations for FPCM decline agreed acceptably with measured data as reflected by the determination coefficient (r2 = 0.51). According to the analysed data, the slope value (0.50) may indicate that the meta-model could tend to overestimate the decline on FPCM, particularly on the low range, but there are insufficient data at the low end to confirm this trend.

The meta-model was also tested for meat systems by comparing the estimated values with observed measurements from a study of Ames and Brink (1977) on growing lambs exposed to different ambient temperatures (-5 to 35º). The meta-model estimations for average daily gain (ADG) agree reasonably well ($r2 = 0.92$, slope=0.78) with the measured data (Figures 14 and 15) although it seems the meta-model tends generally to overpredict ADG.

This could be attributed, in part, to the system applied to estimate energy requirements for sheep itself. In this case, the estimations are based on AFRC, 1993. Although it is a robust and internationally recognised method, it seems AFRC may underestimate energy requirements for small ruminants when compared to other feeding systems (Cannas, 2014). In our meta-model this would lead to a surplus of energy available for growing, and therefore, to an overestimation of daily weight gain. Besides, difficulties on adjusting precisely the fleece depth in shorn lambs also could generate discrepancies in this specific case, as it seems to be a very sensitive value when the meta-model estimates energy requirements under cold conditions.

In addition to this, uncertainty defining the TNZ may be another important source of discrepancies. From the study of Ames and Brink (1977) it is observed a TNZ around 15ºC (10-20ºC), suggesting a THI_{HS}=19.3 (60%RH) while in studies with similar lambs, higher values, up to 25ºC (THI_{HS}=23.7) have been reported (Ames, 1968; Blaxter 1967). As previously described, in this case the HS thresholds proposed by Marai et al., 2007 are applied, in a first attempt to demonstrate the capabilities of the meta-model. However, the TNZ of small ruminants in every situation can be affected by a number of factors that may not always be captured due to the lack of data.

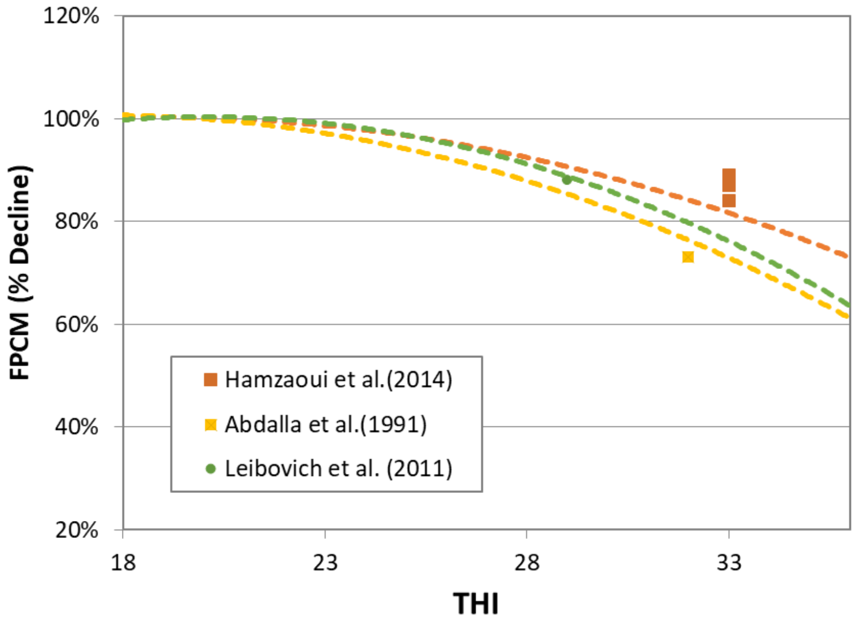

Figure 12. Estimated (dotted lines) vs measured reduction (%) of FPCM of dairy small ruminants under heat stress (Datasets from Abdalla et al 1993; Hamzaoui et al 2014; Leibovich et al 2011)

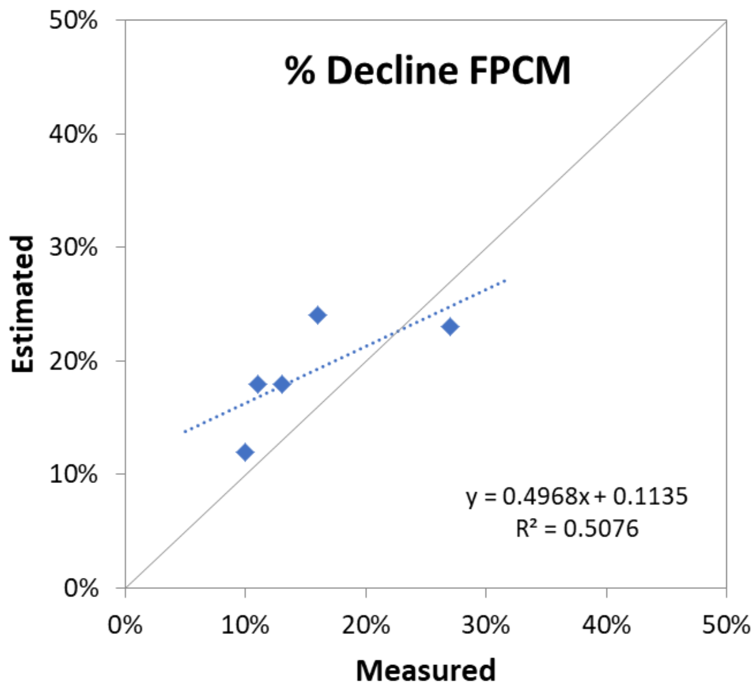

Figure 13. Estimated vs measured reduction (%) of FPCM of dairy small ruminants under heat stress (Datasets from Abdalla et al 1993; Hamzaoui et al 2014; Leibovich et al 2011)

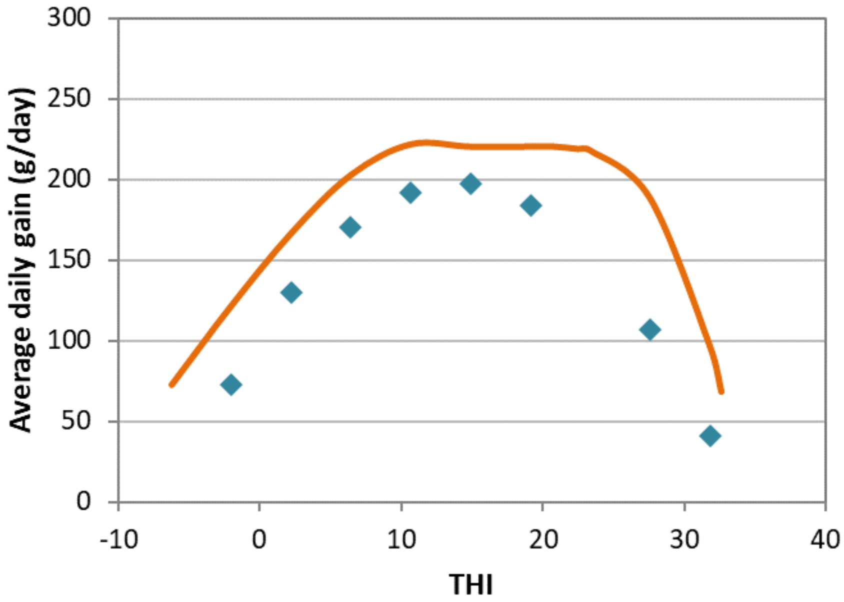

Figure 14. Estimated (line) vs measured average daily gain of growing lambs under heat stress (Datasets from Ames and Brink, 1977)

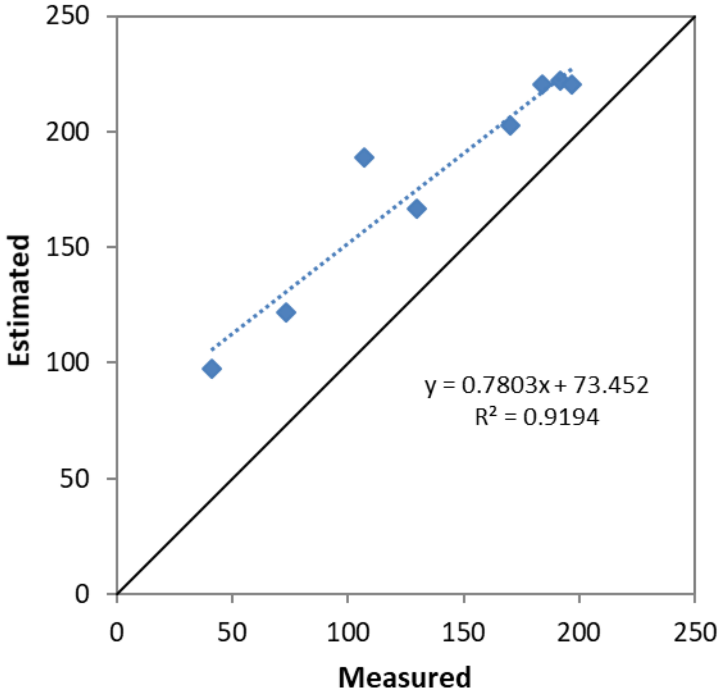

Figure 15. Estimated vs measured average daily gain of growing lambs under heat stress (Datasets from Ames and Brink, 1977)

2.3 Approach 2: Empiric meta-modelling

In this approach, the effect of weather conditions on productivity and health of animals is assessed using on farm data together with weather information from the closest meteorological station. Estimates of losses in traits included in extensive recording programmes can be obtained by fitting functions that associate farm records of animals with changes in the heat load endured by the animals. Given that data available to estimate losses are obtained in farms for breeding or management purposes and not under experimental conditions designed to measure the effect of heat load, environmental factors affecting the traits, such as differences in lactation state, herd management, age of animals at recoding, etc., need to be accounted for when estimating the effect of thermal loads. The basic statistical model used in these studies can be defined as:

$$y = EN + f(TL) + e \qquad (8)$$

, where y is the trait of interest (milk production and milk quality, weight or growth, fertility, etc); EN is the environmental effects that we know affect y apart from the thermal load and can be considered as environmental noise for the parameters of interest; f(TL) is a function describing the effect of thermal load (TL) on y and e is the residual effect that determine the value of y once EN and TL have been discounted. Thermal load can be measured by temperature or an index combining temperature and humidity (THI). Several of such indices have been developed (by NRC (1971), massively used in cattle studies or by Finocchiaro et al. (2005), used in sheep studies)

Basically, two type of functions have been used to estimate the parameters that define the relationship between thermal loads and productivity. Originally, Misztal (1999) proposed a 'Broken Line' (BL) function to describe the response to increasing heat, modelling a thermoneutral region, where no response to changes in thermal load is observed, up to a thermal stress point, followed by the thermal stress region characterised by a linear response of decay in the trait of interest.

$$f(TL) = \begin{Bmatrix} 0, if\ TL \leq To \\ b(TL - To), otherwise \end{Bmatrix} \qquad (9)$$

, where b is the slope of response to temperature increases and To is the thermotolerance threshold.

This approach has been extensively used to measure heat stress effects on milk traits, fertility or growth, mainly in cattle (Ravagnolo et al., 2000; Sánchez et al., 2009; Bernabucci et al., 2014; Hammami et al., 2015; Bradford et al., 2016), but also in sheep (Finocchiaro et al., 2005) and pigs (Zumbach et al., 2008; Bloemhof et al., 2012; Sevillano et al., 2016). The main advantage of this procedure is that response to heat stress is defined only by two parameters, the thermotolerance threshold (To) and the linear regression coefficient of response (b) after the threshold. Estimation of To can be attained by using different statistical methods aiming at finding break points in a series of values of a variable that change with respect to values of another longitudinal variable. The use of the approach suggested by Muggeo (2003, 2008) has been followed in some studies dealing with heat stress thresholds (Ramón et al., 2016, Carabaño et al., 2016). However, locating the thermal threshold is not always easy using field data, which provide far from smooth patterns that link TL with the trait of interest. Thus, the algorithms that search for breaking points have been found often to fail in locating the stress threshold using point estimates of thermal load effects on the trait as data to feed the algorithm (Carabaño et al., 2016). Sophisticated statistical approaches have also been developed to jointly estimate threshold and slope in the BL approach for individual curves of response to thermal loads (Sánchez et al., 2009). Problems associated with bad convergence of the algorithms of estimation of heat stress thresholds have been reported in those studies. Thus, in most applications of the BL model, the value of the threshold is established a priori by visual inspection of the estimated patterns of response of the trait to increasing values of the TL and then used to estimate the slope of this response after the threshold.

Alternatively, smoother continuous functions, mainly polynomials, have been used to fit the response function, f(TL). A normalized base of polynomials, such as the Legendre polynomials have been used in several applications (Brügemann et al., 2011, Carabaño et al., 2014, Ramón et al., 2016)

$$f(TL) = \sum_{i=0}^{q} b_i\, Z_i(TL), \qquad (10)$$

,where bi are regression coefficients, Zi(TL) are the covariates of the Legendre polynomials evaluated at value TL of the thermal load.

Advantages of this approach are the availability of a number of statistical packages that can be used to solve for the regression coefficients, the use of a more flexible model that account for changes in slope after the comfort region and a smoother transition from the thermoneutral to the stress region, in comparison with the BL approach that considers a an abrupt point change from comfort to stress and a constant response after the threshold irrespective of the TL. Using the algorithms to detect change points in trends as the ones previously mentioned, a thermotolerance threshold can be suggested. Given the smoother nature of the response provided by the continuous function, identification of the threshold is more easily attained than in the case of locating a threshold from an unstructured response such as the one provided by point estimates of the effect of TL values. On the other hand, polynomials may show erratic behavior at the extremes of the longitudinal variable scale when the amount of information in these regions is small.

In WP1 of iSAGE, both approaches have been applied to estimate response to increasing heat loads (temperature or THI) for milk production traits and artificial insemination (AI) outcome for sheep and goat breeds raised under intensive or semi-intensive farming systems.

For milk traits, the general model to estimate the response curve was:

$$y_{ijklmn} = FY_i + P\text{-}DIM_j + TB_k + f(TL_l) + animal_m + e_{ijklmn} \qquad (11)$$

Where, yijklmn is the daily milk, fat or protein yield in the day of milk recording, FY is the combination of flock and year of recording, P_DIM is the combination of parity (1, 2, 3+) and days in milk class (10 days classes), TB is the type of birth (single, double or triple), f(HL) was, alternatively, a class effect (with one class per degree of temperature or per unit of THI) or a cubic Legendre polynomial (Leg3) and animal was the animal effect, as random effect with independent levels (no genetic relationships).

For results of AI, the model was

$$y_{ijklmn} = FY_i + Age\_ewe_j + Age\_ram_k + PL_l + MS_m + f(TL_n) + ewe_o + ram_p\ e_{ijklmnopq} \qquad (12)$$

, where y is the AI outcome (0=failure, 1=success), Age_ewe/_ram is the class of age of the ewe and the ram, PL is the class of productive level of the ewe (evaluated from the predicted genetic merit for the ewes in the last available genetic evaluation of the breed), MS is the mating season, ewe and ram are the female and male involved in the AI and e is the residual term. As for the productive traits, f(TL) was the thermal load effect defined as a class effect or by a BL or Leg3 regressions.

Class and Leg3 models were solved using the REMLf90 programme of the BLUPf90 package (Misztal et al. 2002). Threshold and slopes where searched with the Segmented package of R (Muggeo et al., 2008) using estimates of the TL effect estimated by REMLf90. An example for Manchega sheep is shown in figure 16 describing the climate responses curves obtained for a production (fat yield; 16a) and functional (fertility;16b) traits using BL and LEG3 adjustments.

Figure 17 shows a scheme of the conceptual integration of the meta-model into the last stage of the farm modelling framework. An overview of the climate responses curves obtained for the different typologies analyzed is shown through Figure 18 and Table 4.

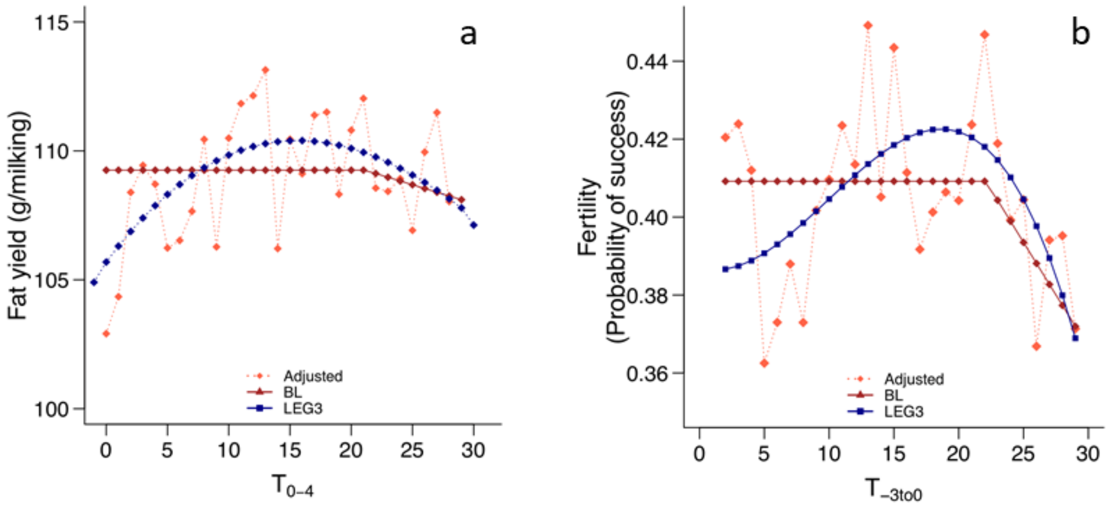

Figure 16a,b. Climate responses curves for a production (fat yield; A) and functional (fertility; B) traits using the two modelling approaches explained above: the broken-line (BL; brown line) and the polynomial (LEG3; blue line) adjustments.

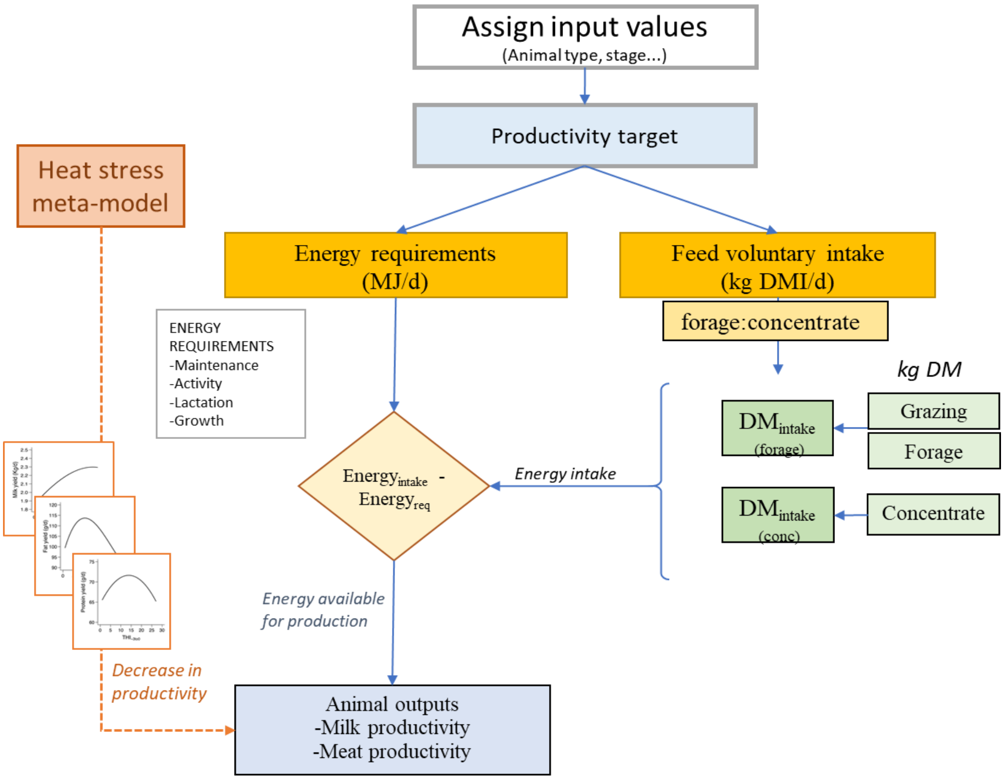

Figure 17. Integration of the heat stress meta-model (approach 2) into the farm modelling framework (SIMS$_{SR}$) to account for potential reduction in productivity.

<table>
<tr><th></th><th>Intensive dairy sheep</th><th>Semi-intensive dairy sheep</th><th>Intensive dairy goat</th><th>Semi-intensive dairy goat</th></tr>
<tr><td></td><td>Assaf</td><td>Manchega</td><td>Murciano-Granadina</td><td>Florida</td></tr>
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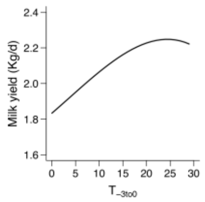
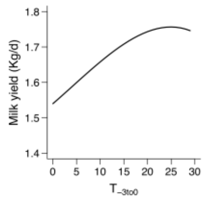
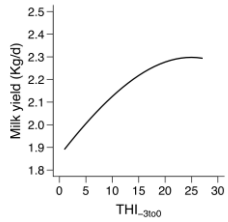
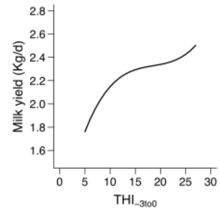
<td></td>
<td></td>
<td></td>
<td></td></tr>
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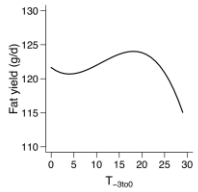
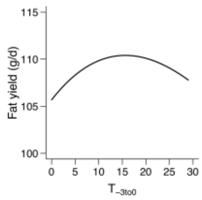
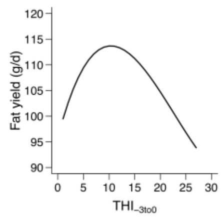
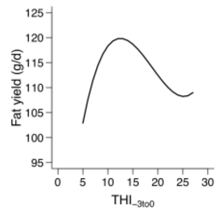
<td></td>
<td></td>
<td></td>
<td></td></tr>
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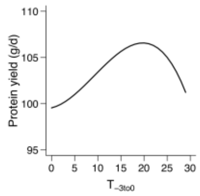
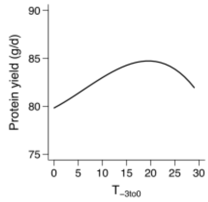
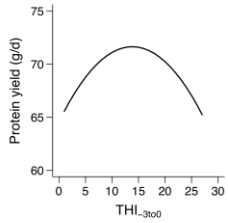
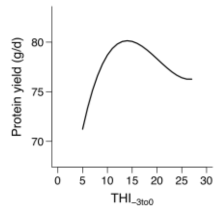
<td></td>
<td></td>
<td></td>
<td></td></tr>
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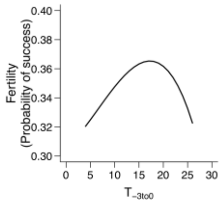
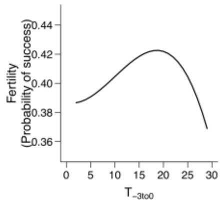
<td></td>
<td></td>
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Figure 18. Climate-performance response curves for the main productive and reproductive traits in sheep and goat species in Europe. Showed curves were drawn from the solutions of a cubic polynomial adjustment.

Table 4. Estimates of heat tolerance threshold (To) and productive and reproductive losses (Slope of decrease in the trait per degree of thermal load) under the broken line (BL) and cubic Legendre polynomial (LEG3) approaches in sheep and goat species in Europe.

Typology	Breed	Climate variable[1]	Trait[2]	BLclass+Segmented		LEG3+Segmented				
				To (ºC)	Slope (unit/ºC)	To (ºC)	Slope at (To+2) (unit/ºC)	Slope at (To+4) (unit/ºC)	Slope at (To+6) (unit/ºC)	Slope at max TL (unit/ºC)
Intensive Dairy sheep	Assaf	THI$_{-3to0}$	Milk	-	-	70	-2.93	-5.92	-9.15	-12.6
			Fat	-	-	61	-0.11	-0.23	-0.36	-1.42
			Protein	-	-	64	-0.14	-0.27	-0.42	-1.14
			Fertility	-	-	-	-	-	-	-
		T$_{-3to0}$	Milk	-	-	25	-7.2	-12.8	-18.8	-21.9
			Fat	20	-0.65	18	-0.25	-0.49	-0.89	-2.88
			Protein	-	-	21	-0.40	-0.68	-1.00	-1.95
			Fertility	20	-0.95	22	-0.77	-1.07	-1.41	-1.59
Semi-intensive dairy sheep	Manchega	THI$_{-3to0}$	Milk	22.0	-38.9	20.5	0.32	-4.13	-	-6.32
			Fat	12.0	-0.14	18.6	-0.24	-0.35	-0.45	-0.50
			Protein	16.9	-0.39	20.5	-0.48	-0.78	-	-0.92
			Fertility	21.0	-1.40	20.9	-0.50	-1.00	-1.70	-1.70
		T$_{-3to0}$	Milk	27.6	-29.75	26.3	-2.81	-9.93	-	-9.93
			Fat	14.0	-0.06	22.3	-0.25	-0.30	-0.34	-0.67
			Protein	17.8	-0.14	22.5	-0.23	-0.37	-0.52	-1.25
			Fertility	22.3	-1.10	23.6	-0.50	-1.00	-1.30	-1.30
Semi-extensive dairy sheep	Latxa	THI*	Milk	17.3	-1.73	13.03	-0.79	-1.15	-	-2.34
			Fat	-	-	-	-	-	-	-0.08
			Protein	15.0	-1.02	7.8	-0.07	-0.12	-0.18	-0.35
		T*	Milk	17.0	-5.52	12.2	-0.54	-1.61	-2.81	-5.92
			Fat	-	-	-	-	-	-	-1.15
			Protein	9.4	-0.20	5.13	-0.06	-0.11	-0.15	-0.35
Intensive dairy goat	Murciano-Granadina	THI$_{-3to0}$	Milk	-	-	20.39	0.00	0.00	-0.003	-0.003
			Fat	19.5	-3.68	14.6	-1.32	-1.50	-1.59	-1.45
			Protein	19.1	-0.75	14.7	-1.20	-1.42	-1.55	-1.45
Semi-intensive dairy goat	Florida	THI$_{-3to0}$	Milk	23.6	0.11	22.3	0.03	0.04	-	0.04
			Fat	12.0	-1.36	12.3	-1.36	-1.28	-0.91	0.62
			Protein	18.7	-1.50	13.6	-1.35	-1.13	-0.63	0.62

[1]T$_{-3to0}$: mean of average daily temperature from 3 days prior to milk recording to the day of milk recording; *: Temperature and THI on the day of control. THI$_{-3to0}$: temperature-humidity index for the same period. The THI index used for the intensive dairy sheep was based on a Fahrenheit scale (a situation with a temperature of 24ºC and 45% of relative humidity corresponds a THI of 70 in Fahrenheit scale and a THI of 21.1 in Celsius scale); [2]Trait units are: milk, fat and protein yield=g/d, Fertility is artificial insemination result as a binary trait (0=AI failure; 1=AI success), slopes are loss in % per unit of THI

2.4 Analysis of strengths and limitations of each approach

The first approach proposes a semi-mechanistic model for capturing the influence of heat stress on sheep and goats productivity. Mechanistic models aim to describe mathematically the relationships between the variables and components of the system. Consequently, they will be constrained by the level of understanding existent about the behaviour of the system. In this case, although a number of studies have analysed the effects of heat stress on small ruminants, there are still some knowledge gaps that would add uncertainty to this approach.

The semi-mechanistic model developed follows an energy balance perspective. The decline on productivity induced by heat stress is attributed to two main causes: a) a reduction on feed intake and b) and increase in energy maintenance requirement. However, the mechanisms causing this productivity decline are not fully understood yet.

While some studies in dairy cows concluded that reduced feed intake explains about 35-50% of milk yield decline (Baumgard and Rhoads, 2013), in the case of dairy small ruminants, some authors suggest that feed intake could have a more relevant influence (Hamzaoui et al., 2014; Salama et al., 2013) although this is a topic still in discussion (Mahjoubi et al. 2014). In conclusion, while the two components considered probably explain most of the decline in productivity, other mechanisms not included in the meta-model could have also an influence, such as lowering blood flow to the udder (Lough et al., 1990) or decreasing the secretion of growth hormone (Mitra et al., 1972).

In addition to this, the available literature about heat stress effects on small ruminants is limited, especially in comparison to dairy and beef cattle (Renaudeau et al., 2012). Because of this, in some aspects the semi-mechanistic relies on relationships from studies on cattle that have been adjusted to be applied on sheep and goats. As all of them are ruminants, they may follow the same principles, but the lack of specific data for sheep and goats in some aspects may involve an additional source of uncertainty.

Applying adequate TNZs in every case can also imply a limitation, as mentioned in previous sections. The influence of some of the factors involves is captured, at least comparativelly (described in section 3.1 below), by increasing or decreasing THI_{HS} thresholds depending on the case. In any case, while the suggested TNZs for sheep and goats are applied by default, the semi-mechanistic model has been developed modularly, so different ranges could be introduced if more adequate data are available.

Nevertheless, the semi-mechanistic meta-model involves some advantages too, of particular importance for the analysis of climate change effects. First, it is more flexible, allowing to conduct tests extrapolating results from conditions not tested before. This could be especially relevant when running future climate change scenarios, involving higher temperatures and extreme events (e.g. heat waves).

Moreover, semi-mechanistic model is designed to capture potential changes on diet and/or forage availability, which links with Task 2.2 (pasture meta-models). As a result, the effects of climate on pasture and forage availability and quality (i.e. digestibility) can be incorporated, as they will have implications in the energy available through feed intake. Similarly, measures related to environmental modifications (e.g. evaporative cooling) and, more interestingly, adaptation changes in the diet (e.g. more energy-dense diets) under heat stress conditions can be tested too.

In contrast the second approach applies empirical/statistical models (regression models) which are based on direct observation and the use of extensive data records and measurements. This type of model are based on a hypothesized relationship between the variables in the data set, where the relationship seeks to best describe the data, and involves some interesting features.

The regression models (approach 2) rely on realized response vs. estimated response to heat stress provided by the semi-mechanistic models (approach 1). This is an attractive feature since it should reflect real losses under field conditions. However, given recording of field data serves other purposes than measuring thermal load effects, many other factors are involved in the determination of the measured traits. Thus, field data contains lots of 'noise' that need to be adjusted using appropriate statistical modelling. Nevertheless, despite of correction for noisy factors, this approach may still yield inaccurate estimates of response. Underestimation of response to heat stress has been found by Freitas et al. (2006) when comparing the use of monthly recording of milk yields, as in current milk recording systems, vs. a weekly recording, which allows for a better adjustment of noise and, thus, capturing a larger proportion of the response to high heat loads.

Empirical models also present some advantages in terms of complexity, being easier to implement and calibrate into a modelling framework. On the other hand, they do not ensure reliable predictions in extrapolated conditions, out of the range of the data used for their development, which may involve some uncertainty when analysing future climate change scenarios, it they involve particularly extreme conditions (e.g. heat waves).

2.5 Model test for the semi-mechanistic meta-model (approach 1)

In order to illustrate the utility of the Approach 1 (Figure 19), which will be integrated into the whole farm model developed under WP4 SIMSsr, this subsection includes some examples to study the impact of thermal stress on animal productivity and dry matter intake. Additionally, we will explore the scope of potential strategies to adapt the animal to this thermal stress to maintain animal productivity and analyse potential synergies/trade-offs with climate change mitigation (i.e. reduction of greenhouse gas {GHG} emissions intensity).

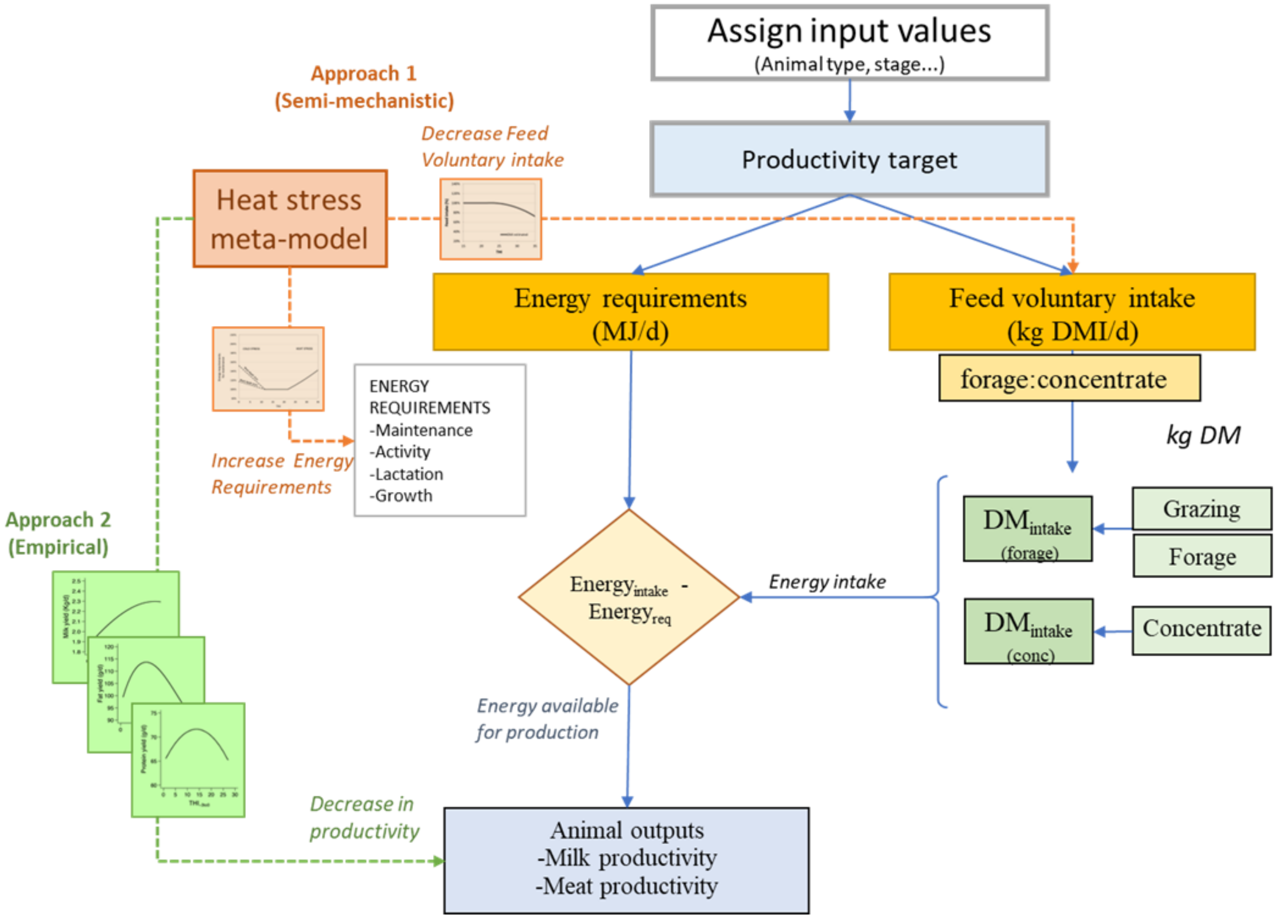

Figure 19. Diagram showing the different level of action for the approach 1 and approach 2 within the SIMSsr farm modelling approach.

Example 1: Effect of heat and cold stress on lamb growth and DM Intake in a meat sheep system:

We chose a meat sheep farming system located in Aragon (north-eastern Spain) (rasa-aragonesa breed), at the catchment basin of the Ebro River. We selected weather from specific periods of different years for simulating: (i) heat stress effect on lambs weight gain for the whole period after weaning (in summer 2017), (ii) a heat wave extreme event (in summer 2015) and (iii) a cold wave extreme event (in winter 2010). Daily temperature is shown for the different situations (Figure 20, 22 and 23). Lambs are fully housed and fed with concentrates, and forage after weaning.

For the first study, we selected a batch of lambs born in May. The period of study involved the period between weaning (13.9 kg LW) to slaughter (22 kg LW) for 260 lambs born in May.

The diet composition is as follows (Table 5):

Table 5. Diet characteristics for the lambs

		GE	DE	ME
FEED	%	MJ/kg DM	MJ/kg DM	MJ/kg DM
Barley	33.6%	18.4	14.8	12.4
Maize	27.3%	18.7	16.1	13.6
Soybean Meal	23.6%	19.7	18.2	13.6
Wheat	6.4%	18.2	15.6	13.1
straw	9.0%	18.2	8	6.5

Figures 20 and 21 show the DM and weight gain reduction results from this first study. Weight gain and DM reduction ranges between 0 to about 18% and 16%, respectively.

Simulated results indicate that aggregated effect of heat stress on lamb growth for this particular example will result in requiring 2 extra days for the lambs to reach the expected slaughter weight (22 kg). Total feed requirements would also increase under heat stress conditions to reach the slaughter weight. Simulated results estimate about almost half a kg of DM feed extra per lamb, which would equate to approximate 228 kg extra of concentrates for 260 lambs (*data not shown*).

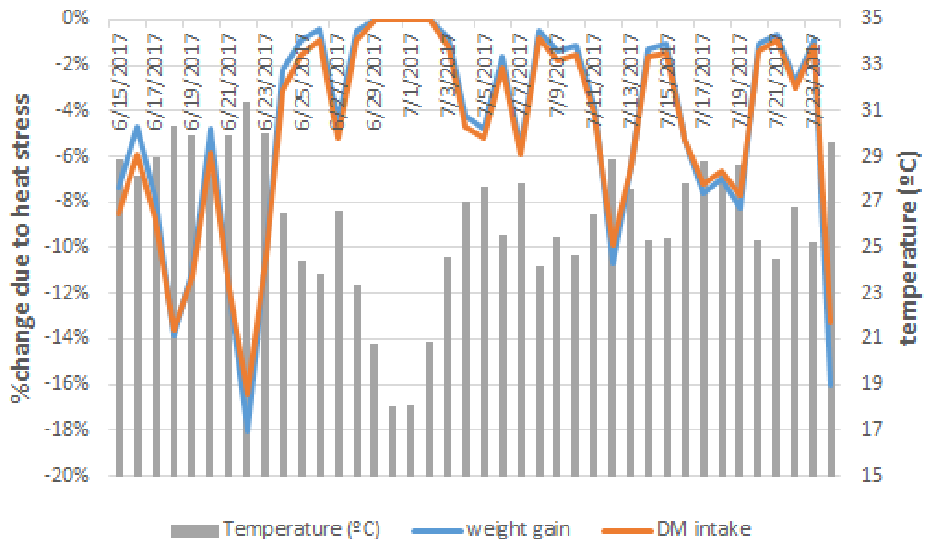

Figure 20. Lamb growth and DM intake reduction (%) for the different days of lambs in the period between weaning and slaughter. Bars indicate daily average temperature (ºC)

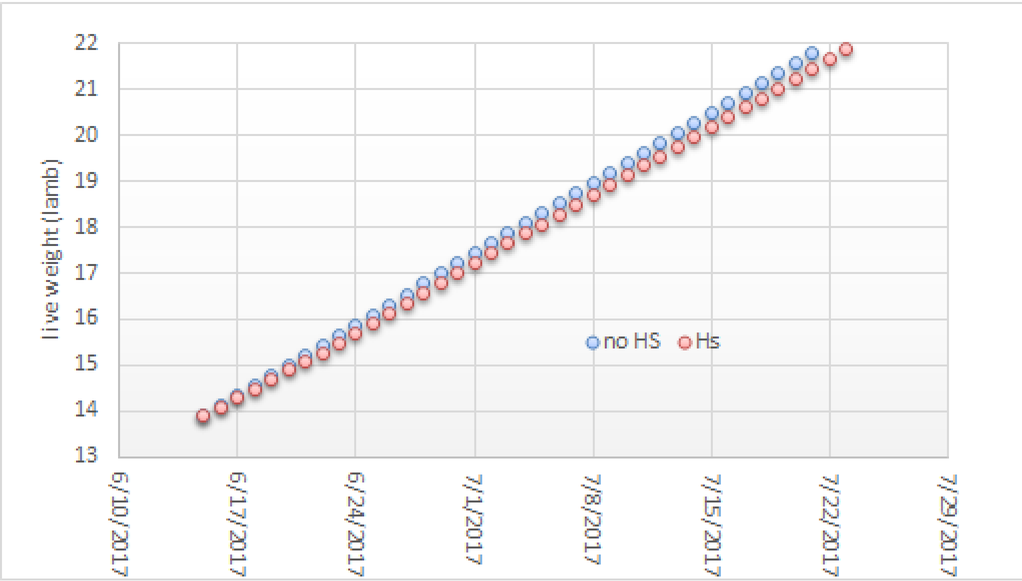

Figure 21. Comparison between lamb growth (kg) considering (red dots) and without considering (blue dots) heat stress effect.

For the second study (**heat wave**), we also selected a batch of lambs born in May. The period of study involved one week of heat stress for lambs born in May for some days between weaning to slaughter in July 2015. The diet composition was also that from Table 5. Results of liveweight gain of lambs under heat vs. non-heat stress are shown in Figure 22.

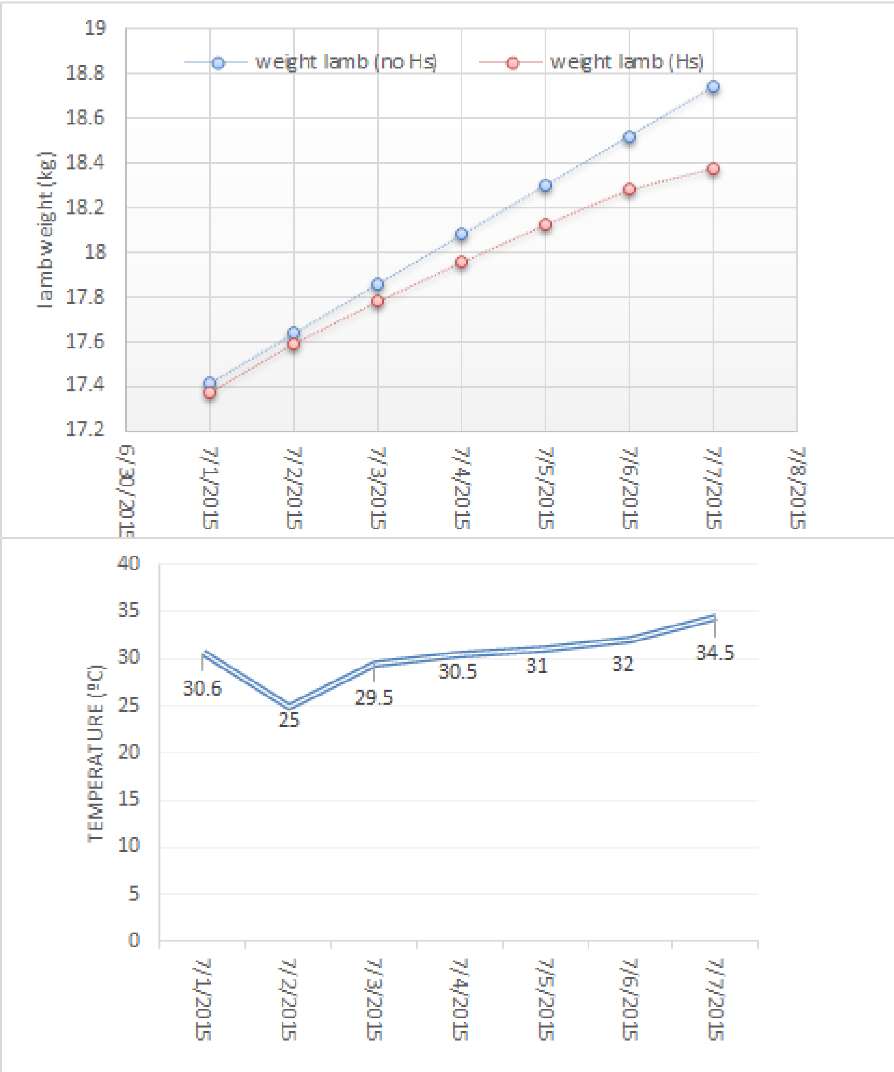

Figure 22. Comparison between lamb growth (kg) considering (red dots) and without considering (blue dots) heat stress effect. Double blue line indicates daily average temperature (ºC) during this period

Simulated results indicate that aggregated effect of heat stress on lamb growth for this week of heat stress will result in a loss in efficiency of feed utilized for growth. In fact, for non-heat vs. heat situation the efficiency will be 265 vs. 249 g-gain/kg DM intake (*data not shown*).

For the third study (**cold wave**), we selected a batch of lambs born in December. The period of study involved 8 days of cold stress for lambs born in December for some days between weaning to slaughter in January 2010. The diet composition was also that from Table 5. Results of liveweight gain of lambs under cold vs. non-cold stress are shown in Figure 23.

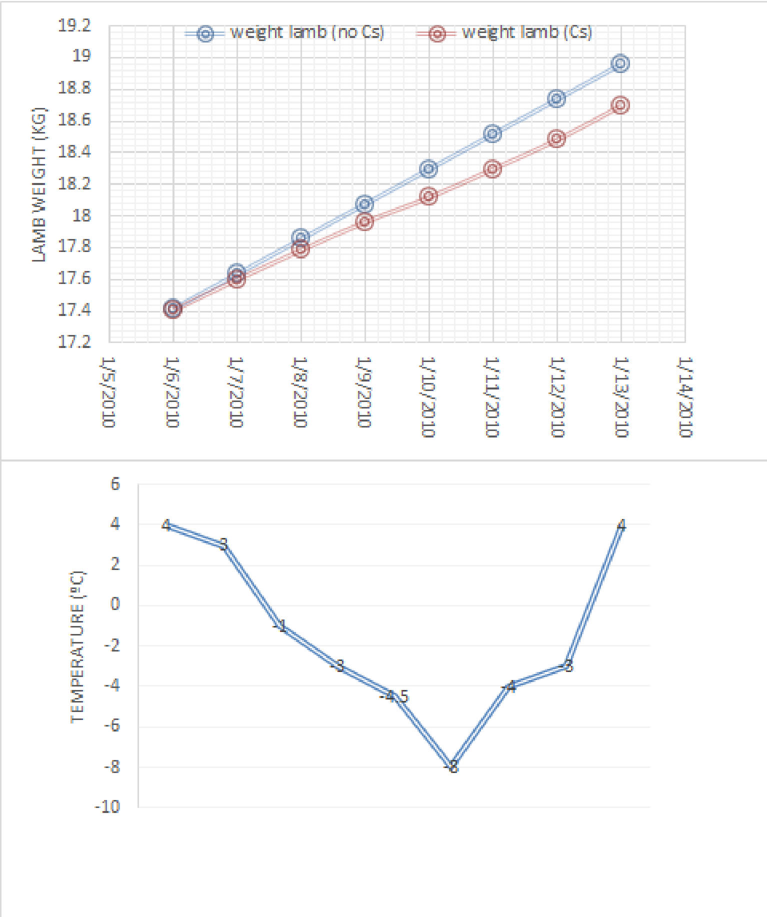

Figure 23. Comparison between lamb growth (kg) considering (red dots) and without considering (blue dots) cold stress effect. Double blue line indicate daily average temperature (ºC) during this period

As with heat stress, simulated results indicate that aggregated effect of cold stress on lamb growth for this week of cold stress will result in a loss in efficiency of feed utilized for growth. In fact, for non-cold vs. heat situation the efficiency will be 264 vs. 211 g-gain/kg DM intake (*data not shown*).

Example 2: Effect of heat stress on milk productivity and DM Intake, adaptation strategies and trade-off synergies with climate change mitigation in lactating ewes:

We chose a dairy sheep farming system located in Castilla la Mancha (central Spain) (manchega breed). We selected a heat wave extreme event of 7 days (in summer 2015). Lactating ewes are fully housed and fed with alfalfa hay and corn as shown in Table 6. Daily temperature is shown for the different situations (Figure 24).

Table 6. Diet characteristics for the manchega lactating ewes

FEED		GE	DE	ME
	%	MJ/kg DM	MJ/kg DM	MJ/kg DM
Alfalfa hay	90%	18.2	10.6	8.4
Corn	10%	18.7	16.1	13.6

The model was run under 4 different scenarios:

- No heat stress: No HS
- Under heat stress: HS (non-adapted)
- Under heat stress but adapted through a higher density diet (replacing 10% DM of hay in the diet ration with soybean meal): HS (adapted-diet)
- Under heat stress but adapted through spraying with water to animals: HS (Adapted-spraying)

Figures 24 shows milk reduction results from this first study for the different scenarios compared with the scenario under no heat stress considered. Non-adapted ewes resulted in losses of up to >20% milk production during the hottest day. Higher energy density feed helped to ameliorate part of the effect of heat stress on DM intake (*data not shown*) and milk productivity. Spraying had a modest effect on reducing the impact of heat stress on the animals.

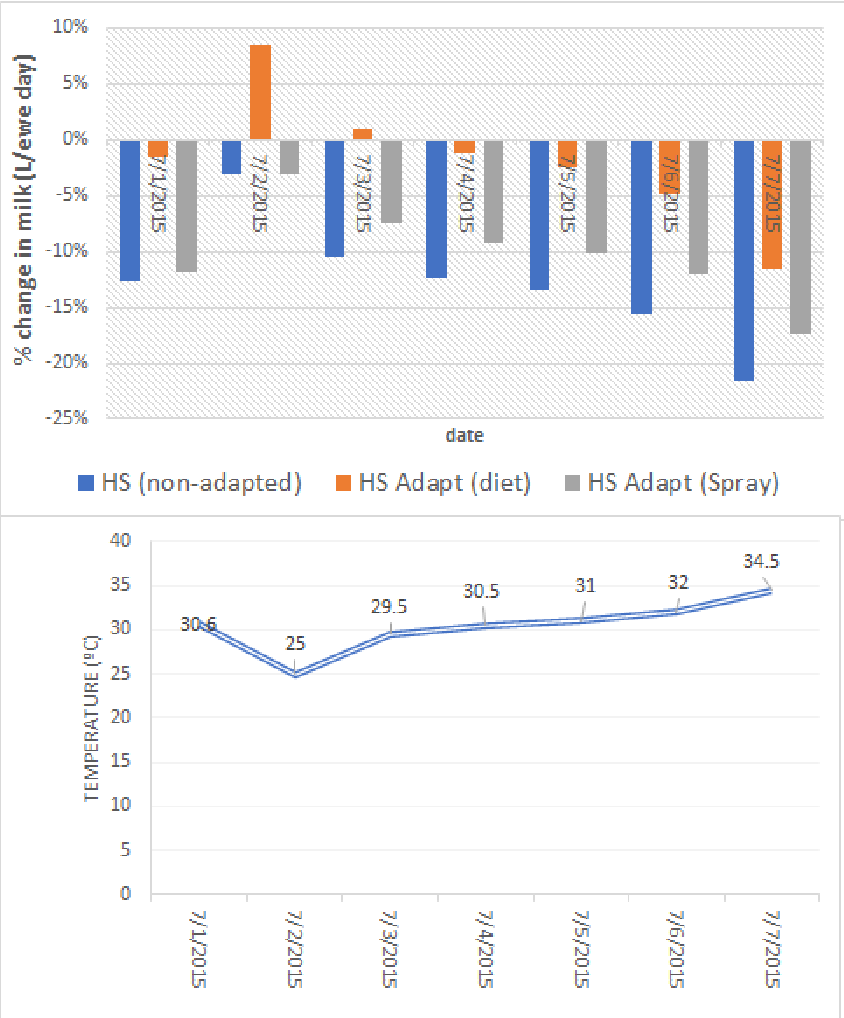

Figure 24. Change in milk productivity (%) for lactating ewes for non-adapted (blue bars), adapted through diet (orange bars) and adapted through spraying the animals (grey bars). Double blue line indicates daily average temperature (ºC) during this period

Aggregated results for this week indicate that animals under heat stress resulted in approximately 11% reduction in milk yield and an extra of 0.12 kg DM intake required per L of milk produced. For the scenario with higher energy density diet, the reduction in milk yield was small (about 2%) compared with the scenario without considering heat stress.

Using the SIMS$_{SR}$ model we also investigated if some of these adaptation strategies could represent a win-win strategy for climate change mitigation (GHG emissions intensity). Hence, we calculated for this period and each scenario the two most important sources of GHG in this type of systems: (i) the enteric CH4 emissions and (ii) the indirect emissions associated to the purchased feed (Figure 25).

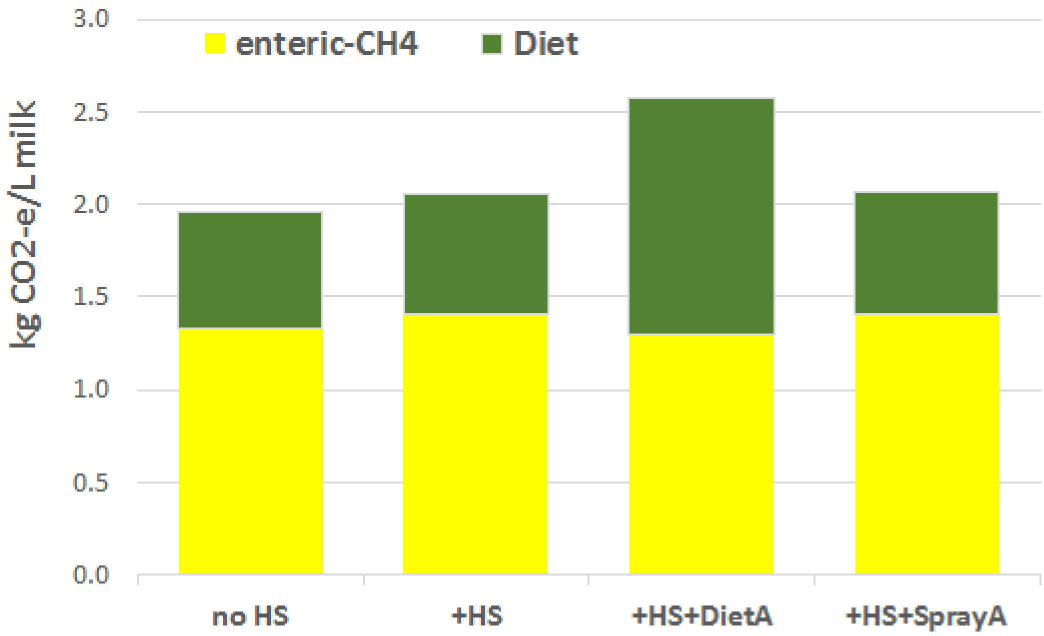

Figure 25. GHG emissions intensity expressed as kg CO_2/L milk for the different scenarios and resulting from (i) enteric CH_4 fermentation (yellow bars) and (ii) pre-farm gate emissions of manufacturing feed from the diet (green bars).

Looking at the enteric CH_4 emission intensity (expressed as kg CO_2-e/L milk), whereas the scenario with a high energy content in the diet (+HS+DietA) reduced about 3% CH_4 emission intensity (*data not shown*) compared with the scenario without considering heat stress (no HS), the non-adapted but impacted scenario (+HS) increased about 5% (*data not shown*) compared with the scenario without considering heat stress (no HS). However, when we include the emissions from manufacturing some of the diet ingredients, the scenario with a high energy content in the diet (+HS+DietA) largely increase the total C footprint due to the large C footprint of soybean ingredient, thus preventing any potential mitigation benefit from the strategy.

3 Effects of thermal stress on animal welfare

3.1 Thermal comfort

To implement animal welfare aspects related to heat stress in the modelling framework developed in WP4 ($SIMS_{SR}$), we propose to design a heat comfort index that could be integrated into a more holistic welfare index approach. The scope of this index is constrained to the farm boundaries (i.e. transport is excluded) and is primarily focused on identifying and valuing the different stages of diminished welfare due to heat stress in small ruminants.

3.1.1 Stages of heat stress

When an animal is subjected to heat stress conditions, a number of different physiological and behavioral responses are triggered in an attempt to cope with the increased heat load, including respiratory rate, heart rate, ruminal movement frequency, rectal and skin temperatures and sweating rate (Marai et al. 2007). The sequence of activation and the intensity of these responses is intimately linked to the level of heat stress suffered by the animal (Figure 26), and some of them have been related to the thermal comfort of the animals through different indexes and score approaches.

Stage I – Mild heat stress

This stage represents the lowest level of heat stress, when environmental temperature rises above the optimal comfort zone. The early response mechanisms to cope with the slight heat load are activated: general vasodilatation, sweating and the respiratory ventilation rate (closed mouth) is elevated moderately to enhance the evaporative heat loss. At this stage, normal body temperature is maintained without difficulty and productivity is not affected.

Stage II – Moderate heat stress

If environmental temperature continues to rise, the evaporative cooling mechanisms of the animals are intensified in order to combat the increased heat load. Respiration rate rises and a rapid shallow breathing is activated, which leads to an increase in the rate of air passage through the upper area of the respiratory tract (Renaudeau et al., 2012). Other changes may be also activated, such as an increase on water consumption (as a result of increased evaporation) or a slight decrease on feed consumption. At this stage, normal body temperature is still maintained, as the intensified mechanisms for heat dissipation can cope with the heat load. However, the responses activated may have implications for the animal fitness, becoming more vulnerable to negative interactions related with nutritional and other external stresses (Silanikove et al., 1997).

Stage III – Severe heat stress

At this stage, previous mechanisms of heat dissipation are intensified and new responses are activated to decrease the internal heat load. Slower deeper open-mouthed panting appears in this phase, which is associated with an increase in the evaporative heat loss capacity by a greater respiratory volume. However, this can also induce alkalosis from the sharp increase in carbon dioxide loss via panting (West, 2003; Srikandakumar et al., 2003) and moderate-to-severe dehydration. In this phase feed intake is reduced and additional mechanisms are activated to lower the basal metabolism, such as a decline in the secretion of calorigenic hormones (e.g. growth hormone). If animals are at a productive stage (growth, lactation) these responses to heat stress are accompanied by negative consequences in productivity, due to reduced performance (Silanikove et al., 2000, Renaudeau et al., 2012). If the rise on heat stress is too sharp, the attempts to dissipate the heat load and maintain homeothermy can be insufficient and as a result, body temperature starts to increase.

Stage IV – Extreme-severe heat stress

If temperature continues rising, evaporative cooling mechanisms are activated at the maximum intensity, inducing heavy panting and maximal sweating. Because of the inability to dissipate heat, the body core temperature increases significantly, resulting in a faster metabolism, which also leads to a higher rate of heat production.

Once these feedback processes are triggered, unless environmental conditions improve or external aid is provided, continued elevation in body temperature can lead the animal to a critical point when it could die due to heat stroke.

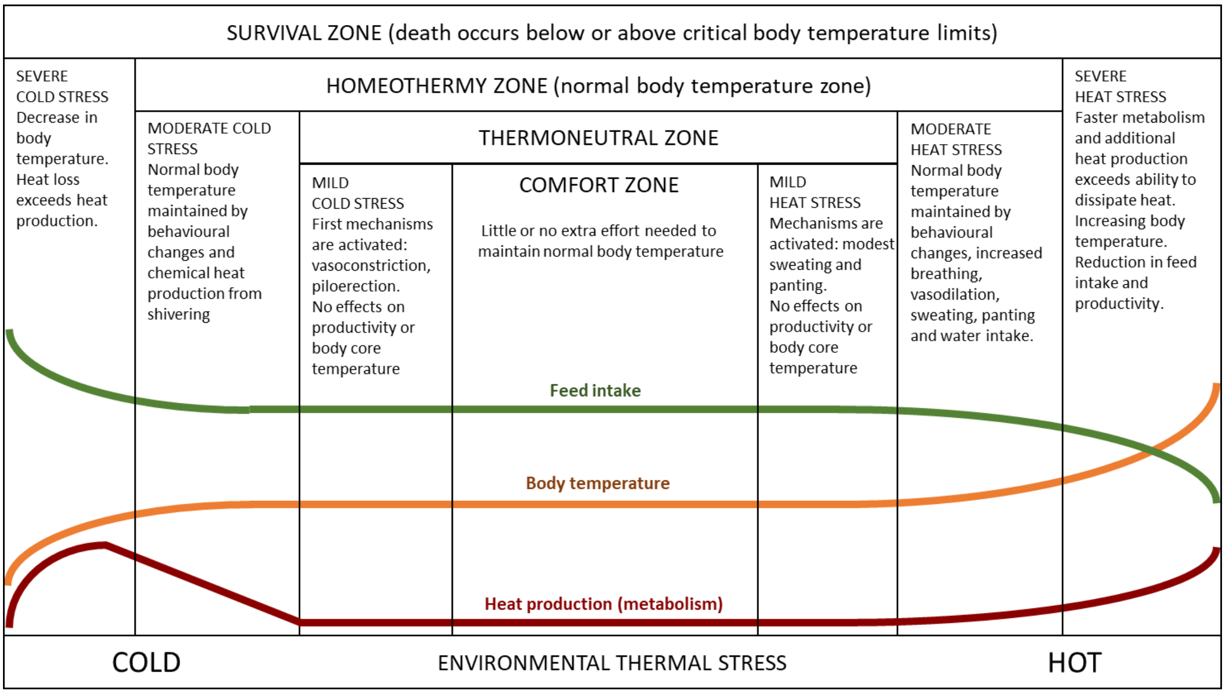

Figure 26. Different levels of response to thermal stress in small ruminants. (Adapted from Silanikove 2000 and NRC 1981).

3.1.2 Thermal comfort index

The THI thresholds and ranges for sheep and goats proposed in section 2.1 (Table 1, Figures 27, 28) were related to the subsequent heat stress stages described in the previous section. Based on the identified heat stress levels and thresholds, a qualitative thermal comfort index is proposed, so it could be integrated in the modelling framework developed in WP4 (SIMS$_{SR}$) for comparison purposes. This approach follows a similar scheme to account for welfare than previous modelling frameworks designed for other species (e.g. SIMS$_{DAIRY}$ (del Prado et al., 2011)). In accordance to that approach, a score is assigned depending on the thermal comfort stage. Based on a positive perspective, the more points the better thermal welfare state is considered (Table 7).

Temperature	% Relative Humidity																				
ºC	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
21	17	18	18	18	18	18	18	19	19	19	19	19	20	20	20	20	20	20	21	21	21
22	18	18	18	18	19	19	19	19	19	20	20	20	20	21	21	21	21	21	22	22	22
23	18	19	19	19	19	19	20	20	20	20	21	21	21	21	22	22	22	22	23	23	23
24	19	19	19	20	20	20	20	21	21	21	21	22	22	22	22	23	23	23	23	24	24
25	19	19	20	20	20	21	21	21	22	22	22	22	23	23	23	24	24	24	24	25	25
26	20	20	20	21	21	21	22	22	22	22	23	23	23	24	24	24	25	25	25	26	26
27	20	20	21	21	21	22	22	22	23	23	24	24	24	25	25	25	26	26	26	27	27
28	21	21	21	22	22	22	23	23	24	24	24	25	25	25	26	26	27	27	27	28	28
29	21	21	22	22	23	23	23	24	24	25	25	25	26	26	27	27	27	28	28	29	29
30	21	22	22	23	23	24	24	24	25	25	26	26	27	27	27	28	28	29	29	30	30
31	22	22	23	23	24	24	25	25	26	26	26	27	27	28	28	29	29	30	30	31	31
32	22	23	23	24	24	25	25	26	26	27	27	28	28	29	29	30	30	31	31	32	32
33	23	23	24	24	25	25	26	26	27	27	28	28	29	29	30	30	31	31	32	32	33
34	23	24	24	25	25	26	26	27	28	28	29	29	30	30	31	31	32	32	33	33	34
35	24	24	25	25	26	27	27	28	28	29	29	30	30	31	32	32	33	33	34	34	35
36	24	25	25	26	26	27	28	28	29	29	30	31	31	32	32	33	34	34	35	35	36
37	25	25	26	26	27	28	28	29	30	30	31	31	32	33	33	34	35	35	36	36	37
38	25	26	26	27	28	28	29	30	30	31	32	32	33	33	34	35	35	36	37	37	38
39	25	26	27	27	28	29	30	30	31	32	32	33	34	34	35	36	36	37	38	38	39
40	26	27	27	28	29	29	30	31	32	32	33	34	34	35	36	36	37	38	39	39	40
41	26	27	28	29	29	30	31	31	32	33	34	34	35	36	37	37	38	39	40	40	41
42	27	28	28	29	30	31	31	32	33	34	34	35	36	37	37	38	39	40	40	41	42
43	27	28	29	30	30	31	32	33	34	34	35	36	37	37	38	39	40	41	41	42	43
44	28	29	29	30	31	32	33	33	34	35	36	37	37	38	39	40	41	42	42	43	44
45	28	29	30	31	32	32	33	34	35	36	37	37	38	39	40	41	42	42	43	44	45

Figure 27. Heat stress levels according to proposed THI thresholds for sheep.

Temperature	% Relative Humidity																				
ºC	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
21	17	18	18	18	18	18	18	19	19	19	19	19	20	20	20	20	20	20	21	21	21
22	18	18	18	18	19	19	19	19	19	20	20	20	20	21	21	21	21	21	22	22	22
23	18	19	19	19	19	19	20	20	20	20	21	21	21	21	22	22	22	22	23	23	23
24	19	19	19	20	20	20	20	21	21	21	21	22	22	22	22	23	23	23	23	24	24
25	19	19	20	20	20	21	21	21	22	22	22	22	23	23	23	24	24	24	24	25	25
26	20	20	20	21	21	21	22	22	22	22	23	23	23	24	24	24	25	25	25	26	26
27	20	20	21	21	21	22	22	22	23	23	24	24	24	25	25	25	26	26	26	27	27
28	21	21	21	22	22	22	23	23	24	24	24	25	25	25	26	26	27	27	27	28	28
29	21	21	22	22	23	23	23	24	24	25	25	25	26	26	27	27	27	28	28	29	29
30	21	22	22	23	23	24	24	24	25	25	26	26	27	27	27	28	28	29	29	30	30
31	22	22	23	23	24	24	25	25	26	26	26	27	27	28	28	29	29	30	30	31	31
32	22	23	23	24	24	25	25	26	26	27	27	28	28	29	29	30	30	31	31	32	32
33	23	23	24	24	25	25	26	26	27	27	28	28	29	29	30	30	31	31	32	32	33
34	23	24	24	25	25	26	26	27	28	28	29	29	30	30	31	31	32	32	33	33	34
35	24	24	25	25	26	27	27	28	28	29	29	30	30	31	32	32	33	33	34	34	35
36	24	25	25	26	26	27	28	28	29	29	30	31	31	32	32	33	34	34	35	35	36
37	25	25	26	26	27	28	28	29	30	30	31	31	32	33	33	34	35	35	36	36	37
38	25	26	26	27	28	28	29	30	30	31	32	32	33	33	34	35	35	36	37	37	38
39	25	26	27	27	28	29	30	30	31	32	32	33	34	34	35	36	36	37	38	38	39
40	26	27	27	28	29	29	30	31	32	32	33	34	34	35	36	36	37	38	39	39	40
41	26	27	28	29	29	30	31	31	32	33	34	34	35	36	37	37	38	39	40	40	41
42	27	28	28	29	30	31	31	32	33	34	34	35	36	37	37	38	39	40	40	41	42
43	27	28	29	30	30	31	32	33	34	34	35	36	37	37	38	39	40	41	41	42	43
44	28	29	29	30	31	32	33	33	34	35	36	37	37	38	39	40	41	42	42	43	44
45	28	29	30	31	32	32	33	34	35	36	37	37	38	39	40	41	42	42	43	44	45

Figure 28. Heat stress levels according to proposed THI thresholds for goats.

Table 7. Thermal comfort index according to heat stress levels.

	SHEEP	GOATS	
Heat stress class	THI range	THI range	Thermal comfort index
Thermoneutral	<22.2	<24.3	4
Mild stress	22.2-23.3	24.3-25.4	3
Moderate stress	23.3-25.6	25.4-27.7	2
Severe stress	25.6-29.3	27.7-31.4	1
Extreme-severe stress	>29.3	>31.4	0

3.1.3 Compound effect of heat stress and additional factors

The vulnerability of sheep and goats to heat stress and signs of thermal stress depend on a number of environmental parameters (mainly temperature and humidity) but also on other factors related with the animal's physiological stage (e.g. pregnancy, lactation), specific breed and nutritional status. Moreover, different strategies can be applied to alleviate heat stress in farm animals (e.g. shelters, shade, ventilation, sprinkles).

In an attempt to integrate the influence of this different aspects into the thermal comfort index proposed, some variation factors are added to the score, so the thresholds are increased or decreased accordingly.

Breed

Breed differences have influence in how well an animal is able to respond to adverse conditions (Barnes et al., 2004). As one example, Alpine goats have shown to be more vulnerable than Nubian goats (Brown et al., 1988).

Northern European breeds are usually the least heat-adaptive because they are normally bred in temperate areas and tend to have shorter bodies and legs; short, thick ears; tight skin, and dense fleeces. In contrast, breeds that are typical in arid and semi-arid environments have a highest thermal comfort zone, as their anatomical and morphological adaptation traits, such as long ears, large body surface, skin thickness and length of hair and high sweating capacity of sweat glands, are better adapted to hot and humid conditions.

In Europe, approximately 76% of dairy sheep and 70% of dairy goats are located in the Mediterranean area, where heat stress conditions are often reached during warm summer months. Some of these local breeds from the Mediterranean area (e.g. Murciano-Granadina) have been shown to have ancestral genetic links to North African goat populations (Manunza et al., 2016) and are being considered as potential exogenous breeding stock to improve productivity under hot and arid conditions (Gaddour et al., 2007).

In conclusion, those breeds that originate in hot, arid or semi-arid areas are considered to cope better with heat stress conditions partly due to their low body mass and low metabolic requirements, which allows them to minimise their water and maintenance requirements. To account for this difference between northern and southern European breeds in the thermal comfort index, the THI threshold is increased in one unit for the case of local breeds from the Mediterranean area (Table 6).

Productivity level

While breeds native of the hottest regions are characterised not only by being adapted to harsh environments (physiologically and nutritionally), they also show low productivity, mainly but not only due to the lack of selection programmes in these regions. The trade-off between heat tolerance and high productivity in dairy ruminants is well known. When the genetic trends for performance under hot conditions are estimated from historical milk records and weather information in dairy ruminant populations, a continuous deterioration of heat tolerance paired with the increasing trend in milk production has been observed not only for highly selected Holstein cattle but also for local breeds of small ruminants (Carabaño et al., 2017).

Therefore, although Mediterranean breeds can be considered more tolerant to heat stress, artificial selection to increase milk yield has been shown to reduce heat tolerance in dairy sheep (Finocchiaro et al., 2005, Ramón et al., 2016) and dairy goats (Menéndez-Buxadera et al., 2016), which supports the idea that selection of high yielding animals that are less sensitive to thermal stress poses physiological challenges. To capture in the thermal comfort index, at least comparatively, the influence of productivity level on the sensitivity of dairy animals to heat stress, the THI threshold is corrected (decreased) depending on the level of production (Table 6).

Environmental modifications

Different strategies can be used to mitigate the effects of hot conditions on the animal welfare. Providing physical protection with artificial or natural shade is one of the most cost-effective measures. Garrett et al (1967) reported that shade may reduce more than 30% of all the heat radiated on an animal, consequently decreasing its heat load and ameliorating its thermal comfort under hot environments. A number of studies have reported the benefits in terms of welfare and heat stress suffered that shade have on small ruminants (Al-Tamimi 2007; Alvarez et al., 2013; Caroprese et al., 2012; Nardone et al., 1991; Sevi et al., 2001). In order to account for this effect in the thermal comfort index, the THI threshold is decreased in one unit in the case that animals reared outdoors are not provided shade (Table 6).

There are also a number of strategies related with housing and management that can be applied to reduce heat stress on livestock. Mechanical ventilation, evaporative cooling and spraying are amongst the most effective and feasible measures that have been identified in literature for sheep and goats (Darcan et al., 2007; Renaudeau et al; Sevi et al., 2007). Their potential effect mitigating the environmental heat stress conditions has been accounted by increasing the THI threshold accordingly when these measures are applied. An overview of the compound effect to heat stress of the different factors considered is described in Table 8. An example of the change on THI thresholds for a dairy goat system with adaptation measures is shown in Figure 29 a,b.

Table 8. Compound effect of various factors to heat stress (THI_{HS} thresholds)

Factor	Effect on THI_{HS} threshold
Breed:	
Southern breed	+1
Northern breed	n.a.
Milk productivity:	
>2.5 l/animal·day	-2
1.5-2.5 l/animal·day	-1
<1.5 l/animal·day	n.a.
Adaptation measures:	
Shade	+1
Mechanical ventilation	+0.5
Evaporative cooling	+1
Spraying	+1.5

Temperature	% Relative Humidity																				
ºC	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
21	17	18	18	18	18	18	18	19	19	19	19	19	20	20	20	20	20	20	21	21	21
22	18	18	18	18	19	19	19	19	19	20	20	20	20	21	21	21	21	21	22	22	22
23	18	19	19	19	19	19	20	20	20	20	21	21	21	21	22	22	22	22	23	23	23
24	19	19	19	20	20	20	20	21	21	21	21	22	22	22	22	23	23	23	23	24	24
25	19	19	20	20	20	21	21	21	22	22	22	22	23	23	23	24	24	24	24	25	25
26	20	20	20	21	21	21	22	22	22	22	23	23	23	24	24	24	25	25	25	26	26
27	20	20	21	21	21	22	22	22	23	23	24	24	24	25	25	25	26	26	26	27	27
28	21	21	21	22	22	22	23	23	24	24	24	25	25	25	26	26	27	27	27	28	28
29	21	21	22	22	23	23	23	24	24	25	25	25	26	26	27	27	27	28	28	29	29
30	21	22	22	23	23	24	24	24	25	25	26	26	27	27	27	28	28	29	29	30	30
31	22	22	23	23	24	24	25	25	26	26	26	27	27	28	28	29	29	30	30	31	31
32	22	23	23	24	24	25	25	26	26	27	27	28	28	29	29	30	30	31	31	32	32
33	23	23	24	24	25	25	26	26	27	27	28	28	29	29	30	30	31	31	32	32	33
34	23	24	24	25	25	26	26	27	28	28	29	29	30	30	31	31	32	32	33	33	34
35	24	24	25	25	26	27	27	28	28	29	29	30	30	31	32	32	33	33	34	34	35
36	24	25	25	26	26	27	28	28	29	29	30	31	31	32	32	33	34	34	35	35	36
37	25	25	26	26	27	28	28	29	30	30	31	31	32	33	33	34	35	35	36	36	37
38	25	26	26	27	28	28	29	30	30	31	32	32	33	33	34	35	35	36	37	37	38
39	25	26	27	27	28	29	30	30	31	32	32	33	34	34	35	36	36	37	38	38	39
40	26	27	27	28	29	29	30	31	32	32	33	34	34	35	36	36	37	38	39	39	40
41	26	27	28	29	29	30	31	31	32	33	34	34	35	36	37	37	38	39	40	40	41
42	27	28	28	29	30	31	31	32	33	34	34	35	36	37	37	38	39	40	40	41	42
43	27	28	29	30	30	31	32	33	34	34	35	36	37	37	38	39	40	41	41	42	43
44	28	29	29	30	31	32	33	33	34	35	36	37	37	38	39	40	41	42	42	43	44
45	28	29	30	31	32	32	33	34	35	36	37	37	38	39	40	41	42	42	43	44	45

Temperature	% Relative Humidity																				
ºC	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
21	17	18	18	18	18	18	18	19	19	19	19	19	20	20	20	20	20	20	21	21	21
22	18	18	18	18	19	19	19	19	19	20	20	20	20	21	21	21	21	21	22	22	22
23	18	19	19	19	19	19	20	20	20	20	21	21	21	21	22	22	22	22	23	23	23
24	19	19	19	20	20	20	20	21	21	21	21	22	22	22	22	23	23	23	23	24	24
25	19	19	20	20	20	21	21	21	22	22	22	22	23	23	23	24	24	24	24	25	25
26	20	20	20	21	21	21	22	22	22	22	23	23	23	24	24	24	25	25	25	26	26
27	20	20	21	21	21	22	22	22	23	23	24	24	24	25	25	25	26	26	26	27	27
28	21	21	21	22	22	22	23	23	24	24	24	25	25	25	26	26	27	27	27	28	28
29	21	21	22	22	23	23	23	24	24	25	25	25	26	26	27	27	27	28	28	29	29
30	21	22	22	23	23	24	24	24	25	25	26	26	27	27	27	28	28	29	29	30	30
31	22	22	23	23	24	24	25	25	26	26	26	27	27	28	28	29	29	30	30	31	31
32	22	23	23	24	24	25	25	26	26	27	27	28	28	29	29	30	30	31	31	32	32
33	23	23	24	24	25	25	26	26	27	27	28	28	29	29	30	30	31	31	32	32	33
34	23	24	24	25	25	26	26	27	28	28	29	29	30	30	31	31	32	32	33	33	34
35	24	24	25	25	26	27	27	28	28	29	29	30	30	31	32	32	33	33	34	34	35
36	24	25	25	26	26	27	28	28	29	29	30	31	31	32	32	33	34	34	35	35	36
37	25	25	26	26	27	28	28	29	30	30	31	31	32	33	33	34	35	35	36	36	37
38	25	26	26	27	28	28	29	30	30	31	32	32	33	33	34	35	35	36	37	37	38
39	25	26	27	27	28	29	30	30	31	32	32	33	34	34	35	36	36	37	38	38	39
40	26	27	27	28	29	29	30	31	32	32	33	34	34	35	36	36	37	38	39	39	40
41	26	27	28	29	29	30	31	31	32	33	34	34	35	36	37	37	38	39	40	40	41
42	27	28	28	29	30	31	31	32	33	34	34	35	36	37	37	38	39	40	40	41	42
43	27	28	29	30	30	31	32	33	34	34	35	36	37	37	38	39	40	41	41	42	43
44	28	29	29	30	31	32	33	33	34	35	36	37	37	38	39	40	41	42	42	43	44
45	28	29	30	31	32	32	33	34	35	36	37	37	38	39	40	41	42	42	43	44	45

Figure 29a,b. Heat stress levels according to proposed THI thresholds for goats without (a) and with (b) spraying devices for reducing heat stress.

3.2 Health

The effects of climate change in animal health could be divided in direct and indirect. The formers are those effects associated with environmental factors (e.g. temperature or humidity conditions) that induce changes on the animal physiology, though, for example, thermal stress (metabolic rates, endocrine status, oxidative status, glucose, protein lipid metabolism, liver functionality among others (Sejian et al., 2017). In this case, environmental stress can have an impact on health or the immune system can be affected, making the animals more vulnerable to diseases, as observed in ewes under hot conditions (Sevi and Caroprese, 2012; Sevi et al 2001, 2002)

On the other hand, indirect effects are those that have an effect on the pathogen, vector or other pathways of disease transmission through possible changes in development rates or adaptation mechanism (Van Dijk et al.,2010). Indirect effects involve multiple and diverse types of effects, from impacts on hosts, vectors, or pathogens to the appearance of new diseases, as well as the increasing of resistance to medicine especially to antibiotics.

Important changes have been projected to the diseases of small ruminants due to climate change, such as impacts on microbial communities, spreading vector borne diseases, food borne diseases, host resistance or feed and water scarcity (Rojas Downing et al., 2017). The most relevant were discussed in the Task 3.1, such as gastrointestinal nematode infections (Fox et al., 2015) or effects on mastitis (Sevi et al., 2003).

Depending on the type of disease, the effects of climate change will be different (Figure 30):

1. Infectious diseases: Increasing of thermal threshold of microbial communities (bacteria, protozoan, virus…) or spreading their space.
2. Foodborne diseases: Alterations on food or food ingested could generate some diseases in livestock. Silage, conservation conditions. Example: Listeriosis
3. Vectors: Vector can generation mechanism of adaptation to new climate conditions, with changes in their temporal and spatial distribution, as well as an acclimation to their current habitats with the new climate conditions or changes in their behaviour patterns and changes of vector population. Example: Dipteros & Tickbone diseases
4. Reservoirs
5. Pathways

CLIMATE CHANGE
Changes in temperature, Humidity, etc,..

1. HOSTs (humans, animals, plants...) Ex heat or drought stress = increased susceptibility to disease
2. VECTORs (insects, animals, etc..) Ex. Higher overwintering survival =earlier onset of disease
3. DISEASE AGENT (bacteria, fungi, etc..) Ex. Faster maturation rates in warmer temperatures = more diseases cycles per year)
4. DISEASE RESERVOIRS (birds, etc..) Ex. Range expansion =spread disease to new areas.
5. TRANSMISSION PATHWAYS (Air currents, wind storms, etc) Ex. Wind storms can blow infected insect vectors into new locations

Figure 30. Multiple effects on sheep and goat diseases due to climate change (Source: Greifenhagen et al (2003))

There are different pathways of transmissions of animal diseases, and therefore, the possible effects of climate change will be different on each of them (Table 9). Some diseases are transmitted among animals and from animal to people more or less directly. Other agents can be transmitted through insect vectors, through water or food such as meat or general environmental contamination. In addition to this, changes on climate conditions affect the survival of insect vector and may allow the appearance of diseases that were considered exotic before.

Table 9. Mode of disease transmission

TRANSMISSION MODE	POSSIBLE EFFECTS OF CLIMATE CHANGE
Vector	Lengthened transmission season, increased overwinter survival, range expansion, more frequent transmission
Food	Increased risk of food contamination, increased replication and survival of pathogens, higher incidence of pathogens in animal reservoirs. Ex salmonella
Water	Increased risk of outbreaks because of extreme precipitation events
Direct	Alterations in range and population dynamics of animal reservoirs

A review has been conducted through this task aiming to identify the main diseases affecting small ruminant systems whose incidence or distribution may be affected by climate change (Table A3). Capturing the many different potential risk effects linked to climate change through a single meta-model may not be feasible. However, the main modelling approaches described in literature for predicting animal disease evolution linked to changes on environmental conditions have been identified (Table A4) so they could be implemented into the modelling framework for more specific analysis.

4 References

Abdalla, E.B., Kotby, E.A., Johnson, H.D., 1993. Physiological responses to heat-induced hyperthermia of pregnant and lactating ewes. Small Rumin. Res. 11, 125–134. doi:10.1016/0921-4488(93)90145-8

Agricultural and Food Research Council, 1993. Energy and protein requirements of ruminants: an advisory manual. CAB international.

Al-Dawood, A., 2017. Towards Heat Stress Management in Small Ruminants – A Review. Ann. Anim. Sci. 17, 59–88. doi:10.1515/aoas-2016-0068

Alhidary, I.A., Shini, S., Al Jassim, R.A.M., Gaughan, J.B., 2012. Physiological responses of australian merino wethers exposed to high heat load. J. Anim. Sci. 90, 212–220. doi:10.2527/jas.2011-3972

Al-Tamimi, H.J., 2007. Thermoregulatory response of goat kids subjected to heat stress. Small Rumin. Res. 71, 280–285. doi:10.1016/j.smallrumres.2006.04.013

Alvarez, L., Guevara, N., Reyes, M., Sánchez, A., Galindo, F., 2013. Shade effects on feeding behavior, feed intake, and daily gain of weight in female goat kids. J. Vet. Behav. Clin. Appl. Res. 8, 466–470. doi:10.1016/j.jveb.2013.08.002

Ames, David R. 1968. Normal responses of sheep to acute thermal stress. Ph.D. Thesis. Michigan State University, East Lansing.

Ames, D.R., Nellor, J.E., Adams, T., 1971. Energy balance during heat stress in sheep. J. Anim. Sci. 32, 784–788.

Ames, D.R., Brink, D.R., 1977. Effect of temperature on lamb performance and protein efficiency ratio. J. Anim. Sci. 44, 136–144.

Appleman, R.D., Delouche, J.C., 1958. Behavioral, Physiological and Biochemical Responses of Goats to Temperature, 0° to 40° C. J. Anim. Sci. 17, 326–335.

Babiul, S.; Bowden, TR.; Boyle, D.B.; Wallace, D.B.; Kitching, R.P. 2008. Capripoxviruses: An Emerging Worldwide Threat to Sheep, Goats and Cattle. Transboundary and Emerging Dieases. 55(7):263-72

Barnes, A., Beatty, D., Taylor, E., Stockman, C., Maloney, S., McCarthy, M., 2004. Physiology of heat stress in cattle and sheep. Meat Livest. Aust. 209, 1–36.

Baumgard, L.H., Rhoads, R.P., 2012. Ruminant Nutrition Symposium: ruminant production and metabolic responses to heat stress. J. Anim. Sci. 90, 1855–1865.

Baumgard, L.H., Rhoads Jr, R.P., 2013. Effects of heat stress on postabsorptive metabolism and energetics. Annu. Rev. Anim. Biosci. 1, 311–337.

Bennett, J.W., 1973. Regional body surface area of sheep. J. Agric. Sci. 81, 429–432.

Bernabucci, U., Lacetera, N., Danieli, P.P., Bani, P., Nardone, A., Ronchi, B., 2009. Influence of different periods of exposure to hot environment on rumen function and diet digestibility in sheep. Int. J. Biometeorol. 53, 387–395. doi:10.1007/s00484-009-0223-6

Bernabucci, U., L. Basiricò, P. Morera, D. Dipasquale, A. Vitali, F. Piccioli Cappelli, and L. Calamari. 2015. Effect of summer season on milk protein fractions in Holstein cows. J. Dairy Sci. 98:1815–1827. doi:10.3168/jds.2014-8788

Bhattacharya, A.N., Hussain, F., 1974. Intake and utilization of nutrients in sheep fed different levels of roughage under heat stress. J. Anim. Sci. 38, 877–886.

Bianca, W., 1970. Animal response to meteorological stress as a function of age. Biometeorol. 4, 119–131.

Blaxter, K.L., Graham, N.M., Wainman, F.W., 1959. Environmental temperature, energy metabolism and heat regulation in sheep. III. The metabolism and thermal exchanges of sheep with fleeces. J. Agric. Sci. 52, 41–49.

Blaxter, K. L. 1967. Ed. The Energy Metabolism of Ruminants. Hutchinson and Co., London, England.

Bloemhof, S., A. Kause, E. F. Knol, J. A. M. Van Arendonk, and I. Misztal. 2012. Heat stress effects on farrowing rate in sows: Genetic parameter estimation using within-line and crossbred models. J. Anim. Sci. 90:2109–2119. doi:10.2527/jas.2011-4650

Bradford, H. L., B. O. Fragomeni, J. K. Bertrand, D. A. L. Lourenco, and I. Misztal. 2016. Genetic evaluations for growth heat tolerance in Angus cattle. J. Anim. Sci. 94:4143–4150. doi:10.2527/jas2016-0707

Brasil, H.L., Wechesler, F.S., Júnior, F.B., Gonçalves, H.C., Bonassi, I.A., 2000. Efeitos do Estresse Térmico Sobre a Produção , Composição Química do Leite e Respostas Termorreguladoras de Cabras da Raça Alpina Thermal Stress Effects on Milk Yield and Chemical Composition and Thermoregulatory Responses of Lactating Alpines Goats 29, 1632–1641.

Brown, D.L., Morrison, S.R., Bradford, G.E., 1988. Effects of Ambient Temperature on Milk Production of Nubian and Alpine Goats. J. Dairy Sci. 71, 2486–2490. doi:10.3168/jds.S0022-0302(88)79835-5

Brügemann, K., E. Gernand, U. U. von Borstel, and S. König. 2011. Genetic analyses of protein yield in dairy cows applying random regression models with time-dependent and temperature × humidity-dependent covariates. J. Dairy Sci. 94:4129–4139. doi:10.3168/jds.2010-4063

Cannas, A., 2004. Energy and Protein Requirements. Dairy sheep nutrition. Editors Pulina, G; Bencini, R. CABI publishing.

Carabaño, M. J., K. Bachagha, M. Ramón, and C. Díaz. 2014. Modeling heat stress effect on Holstein cows under hot and dry conditions: Selection tools. J. Dairy Sci. 97:7889–7904. doi:10.3168/jds.2014-8023

Carabaño, M. J., B. Logar, J. Bormann, J. Minet, M.-L., Vanrobays, C. Díaz, B. Tychon, N. Gengler, and H. Hammami. 2016. Modelling heat stress under different environmental conditions. J. Dairy Sci. 99:3798–3814. doi:10.3168/jds.2015-10212

Carabaño, M.J., Ramón, M., Díaz, C., Molina, A., Pérez-Guzmán, M.D., Serradilla, J.M., 2017. Breeding and genetics symposium: breeding for resilience to heat stress effects in dairy ruminants. A comprehensive review. J. Anim. Sci. 95, 1813–1826.

Caroprese, M., Albenzio, M., Bruno, A., Annicchiarico, G., Marino, R., Sevi, A., 2012. Effects of shade and flaxseed supplementation on the welfare of lactating ewes under high ambient temperatures. Small Rumin. Res. 102, 177–185. doi:10.1016/j.smallrumres.2011.07.010

Curtis, S.E., 1983. Environmental management in animal agriculture. Iowa State University Press.

Darcan, N., Güney, O., 2007. Alleviation of climatic stress of dairy goats in Mediterranean climate. Small Rumin. Res. 74, 212–215. doi:10.1016/j.smallrumres.2007.02.007

Denek, N., Can, A., Tufenk, S., Yazgan, K., Ipek, H., Iriadam, M., 2006. The effect of heat load on nutrient utilization and blood parameters of Awassi ram lambs fed different types and levels of forages. Small Rumin. Res. 63, 156–161. doi:10.1016/j.smallrumres.2005.02.017

Dixon, R.M., Thomas, R., Holmes, J.H.G., 1999. Interactions between heat stress and nutrition in sheep fed roughage diets. J. Agric. Sci. 132, 351–359. doi:10.1017/S0021859698006248

Finocchiaro, R., van Kaam, J.B.C.H.M., Portolano, B., Misztal, I., 2005. Effect of Heat Stress on Production of Mediterranean Dairy Sheep. J. Dairy Sci. 88, 1855–1864. doi:10.3168/jds.S0022-0302(05)72860-5

Fox, N.J.; Davidson, R.S.; Marion, G.; Hutchings, M.R. (2015) Modelling livestock parasite risk under climate change.

Freitas, M.S., I. Misztal, J. Bohmanova, and J. West. 2006. Utility of on-and off-farm weather records for studies in genetics of heat tolerance. Livest. Sci. 105:223-228. doi: https://doi.org/10.1016/j.livsci.2006.06.011.

Hammami, H., J. Bormann, N. M'hamdi, H. H. Montaldo, and N. Gengler. 2013. Evaluation of heat stress effects on production traits and somatic cell score of Holsteins in a temperate environment. J. Dairy Sci. 96:1844–1855. doi:10.3168/jds.2012-5947

Gaddour, A., Najari, S., Ouni, M., 2007. Dairy performances of the goat genetic groups in the southern Tunisian. Agric. J. 2, 248–253.

Ganter, M. (2015) Zoonotic risks from small ruminants. Veterinary microbiology 181:53-65

Greifenhagen, S. and Noland, T.L. (2003). A synopsis of known and potential diseases and parasites associated with climate change. Ontario Ministry of Natural Resource, Ontario Forest Research Institute. Forest Research Information Paper. 154: 200

Garrett, W.N., Bond, T.E., Pereira, N., 1967. Influence of shade height on physiological responses of cattle during hot weather. Trans. ASAE 10, 433–434.

Graham, N.M., Wainman, F.W., Blaxter, K.L., Armstrong, D.G., 1959. Environmental temperature, energy metabolism and heat regulation in sheep. I. Energy metabolism in closely clipped sheep. J. Agric. Sci. 52, 13–24.

Gray,J.S.; Dautel, H.; Estrada-Peña, A.; Kahl, O; Lindgren, E.(2009) Effects of climate change on ticks and tick-norne diseases in Europe. Interdiscip Perspect Infect Dis. 2009; 2009: 593232

Hamzaoui, S., Salama, A.A.K., Albanell, E., Such, X., Caja, G., 2013. Physiological responses and lactational performances of late-lactation dairy goats under heat stress conditions. J. Dairy Sci. 96, 6355–6365. doi:10.3168/jds.2013-6665

Hamzaoui, S., 2014. Heat stress responses in dairy goats and effects of some nutritional strategies for mitigation.

Hofman, W.F., Riegle, G.D., 1977. Thermorespiratory responses of shorn and unshorn sheep to mild heat stress. Respir. Physiol. 30, 327–338.

Indu, S., Sejian, V., Naqvi, S.M.K., 2015. Impact of simulated semiarid tropical environmental conditions on growth, physiological adaptability, blood metabolites and endocrine responses in Malpura ewes. Anim. Prod. Sci. 55, 766–776. doi:10.1071/AN14085

Kadzere, C.T., Murphy, M.R., Silanikove, N., Maltz, E., 2002. Heat stress in lactating dairy cows: a review. Livest. Prod. Sci. 77, 59–91.

L., B.D., Morrison, S.R., Bradford, G.E., 1988. Effects of ambient temperature on milk production of Nubian and Alpine goats. J. Dairy Sci. 71, 2486–2490. doi:10.3168/jds.S0022-0302(88)79835-5

Leibovich, H., Zenou, A., Seada, P., Miron, J., 2011. Effects of shearing, ambient cooling and feeding with byproducts as partial roughage replacement on milk yield and composition in Assaf sheep under heat-load conditions. Small Rumin. Res. 99, 153–159. doi:10.1016/j.smallrumres.2011.03.049

Lough, D.S., Beede, D.L., Wilcox, C.J., 1990. Effects of feed intake and thermal stress on mammary blood flow and other physiological measurements in lactating dairy cows. J. Dairy Sci. 73, 325–332.

Lu, C.D., 1989. Effects of heat stress on goat production. Small Rumin. Res. 2, 151–162. doi:10.1016/0921-4488(89)90040-0

McMahon, C; Gordon, A.W.; Edgar, H.W.J; Hanna, R.E.B.; Brenna, G.P.; Fairweather, I. 2012, The effects of climate change on ovine parasitic gastroenteritis determined using veterinary surveillance and meterological data for Northern Ireland over the period 1999-2009. Veterinary parasitology 190:167-177.

McMahon, C.; Edgar, H.W.J; Hanna, R.E.B.; Ellison, S.E.; Flanagan, A.M.; McCoy, M; Kajugy, P.E.; Gordon, A.W.; Irwin, D; Barley, J.E.; Malone, F.E.; Brennan, G.P.; Fairwerather, I. 2016, Liver fluke control on sheep farms in Northern Ireland: A survey of changing management practice in relation to disease prevalence and perceived triclabendazole resistance. Veterinary pasasitology 216:72-83.

Mahjoubi, E., Amanlou, H., Mirzaei-Alamouti, H.R., Aghaziarati, N., Yazdi, M.H., Noori, G.R., Yuan, K., Baumgard, L.H., 2014. The effect of cyclical and mild heat stress on productivity and metabolism in Afshari lambs. J. Anim. Sci. 92, 1007–1014.

Manunza, A., Noce, A., Serradilla, J.M., Goyache, F., Martínez, A., Capote, J., Delgado, J.V., Jordana, J., Muñoz, E., Molina, A., 2016. A genome-wide perspective about the diversity and demographic history of seven Spanish goat breeds. Genet. Sel. Evol. 48, 52.

Marai, I.F.M., El-Darawany, A.A., Fadiel, A., Abdel-Hafez, M.A.M., 2007. Physiological traits as affected by heat stress in sheep-A review. Small Rumin. Res. 71, 1–12. doi:10.1016/j.smallrumres.2006.10.003

Menéndez-Buxadera, A., Molina, A., Arrebola, F., Clemente, I., Serradilla, J.M., 2012. Genetic variation of adaptation to heat stress in two Spanish dairy goat breeds. J. Anim. Breed. Genet. 129, 306–315. doi:10.1111/j.1439-0388.2011.00984.x

Menéndez-Buxadera, A., Serradilla, J.M., Arrebola, F., Clemente, I., Castro, J.A., Osorio, J., Torres, R., Molina, A., 2014. Genetic variation for tolerance to heat stress in dairy small ruminants : Results obtained in Spain. Options Méditerranéennes. Ser. A Mediterr. Semin. 135–139.

Menéndez-Buxadera, A., Serradilla, J.M., Molina, A., 2014. Genetic variability for heat stress sensitivity in Merino de Grazalema sheep. Small Rumin. Res. 121, 207–214. doi:10.1016/j.smallrumres.2014.06.007

Mishra, R.P., 2009. Role of housing and management in improving productivity efficiency of goats. Goat Prod. milk meat. Cent. Inst. Res. Goats (CIRG), India, 45.

Misztal, I. 1999. Model to study genetic component of heat stress in dairy cattle using national data. J. Dairy Sci. 82 (E. Suppl. 1): E32.

Misztal, I., S. Tsuruta, T. Strabel, B. Auvray, T. Druet, and D. H. Lee. 2002. BLUPF90 and related programs. Commun. No. 28-07 in Proc. 7th World Congr. Genet. Appl. Livest. Prod., Montpellier, France.

Mitra, R., Christison, G.I., Johnson, H.D., 1972. Effect of prolonged thermal exposure on growth hormone (GH) secretion in cattle. J. Anim. Sci. 34, 776–779.

Muggeo, V. M. R. 2003. Estimating regression models with unknown breakpoint. Stat. Med. 22:3055–3071.

Muggeo, V. M. R. 2008. Segmented: An R package to fit regression models with broken-line relationships. R News 8:20–25.

Mysterud, A; Stigum, V.M.; Seland, I.V.; Herland, A.; Easterday, W.R.; Jore, S.; Osteras, O; Viljugren, H (2018). Tick abundance, pathogen prevalence, and disease incidence in two contrasting regions at the northern distribution range of Europe. Parasites & Vectors 11:309.

National Research Council. 1971. A Guide to Environmental Research on Animals. Natl. Acad. Sci., Washington, DC.

National Research Council, 1981. Effect of environment on nutrient requirements of domestic animals. National Academies Press.

National Research Council, 2001. Nutrient requirements of dairy cattle: 2001. National Academies Press.

Nikitchenko, I.N., Plyaschenko, S.I., Zenkov, A.C., 1988. Stresses and productivity of farm animals.

Olsson, K., Dahlborn, K., 1989. FLUID BALANCE DURING HEAT STRESS IN LACTATING GOATS. Q. J. Exp. Physiol. 645–659.

Peana, I., Fois, G., Cannas, A., 2007. Effects of heat stress and diet on milk production and feed and energy intake of Sarda ewes. Ital. J. Anim. Sci. 6, 577–579. doi:10.4081/ijas.2007.1s.577

Pulina, G., Macciotta, N., Nudda, A., 2005. Milk composition and feeding in the Italian dairy sheep. Ital. J. Anim. Sci. 4, 5–14.

Ramón, M., Díaz, C., Pérez-Guzman, M.D., Carabaño, M.J., 2016. Effect of exposure to adverse climatic conditions on production in Manchega dairy sheep. J. Dairy Sci. 99, 5764–5779.

Ravagnolo, O., I. Misztal, and G. Hoogenboom. 2000. Genetic component of heat stress in dairy cattle, parameter estimation. J. Dairy Sci. 83:2126–2130. doi:10.3168/jds.S0022-0302(00)75095-8

Renaudeau, D., Collin, A., Yahav, S., de Basilio, V., Gourdine, J.L., Collier, R.J., 2012. Adaptation to hot climate and strategies to alleviate heat stress in livestock production. Animal 6, 707–728. doi:10.1017/s1751731111002448

Robertshaw, D., Dmi'el, R., 1983. The effect of dehydration on the control of panting and sweating in the black Bedouin goat. Physiol. Zool. 56, 412–418.

Rojas-Downing, M ; Pouyan A; Timothy Harrigan, S A; Woznicki (2017) Climate change and livestock: Impacts, adaptation, and mitigation. Climate Risk Management. 16, 145-163.

Romero, F., Molina, A., González, O., Clemente, I., Arrebola, F., Menéndez-Buxadera, A., 2008. Resultados preliminares del efecto de la temperatura y humedad relativa sobre la producci??n de leche y sus componentes en cabras de raza Payoya. ITEA Inf. Tec. Econ. Agrar. 104, 243–248.

Ronchi, B., Nardone, A., Boyazoglu, J.G., 1991. Animal husbandry in warm climates. doi:10.1016/j.seppur.2014.07.028

Salama, A.A.K., Caja, G., Hamzaoui, S., Badaoui, B., Castro-Costa, A., Façanha, D.A.E., Guilhermino, M.M., Bozzi, R., 2014. Different levels of response to heat stress in dairy goats. Small Rumin. Res. 121, 73–79. doi:10.1016/j.smallrumres.2013.11.021

Salem, M.H., Yousef, M.K., El-Sherbiny, A.A., Khalil, M.H., 1982. Physiology of sheep and goats in the tropics.

Sánchez, J. P., I. Misztal, I. Aguilar, B. Zumbach, and R. Rekaya. 2009. Genetic determination of the onset of heat stress on daily milk yield in US Holstein cattle. J. Dairy Sci. 92:4035–4045. doi:10.3168/jds.2008-1626

Sano, H., Ambo, K., Tsuda, T., 1985. Blood Glucose Kinetics in Whole Body and Mammary Gland of Lactating Goats Exposed to Heat. J. Dairy Sci. 68, 2557–2564. doi:10.3168/jds.S0022-0302(85)81137-1

Sevi, A., Annicchiarico, G., Albenzio, M., Taibi, L., Muscio, A., Dell'Aquila, S., 2001. Effects of solar radiation and feeding time on behavior, immune response and production of lactating ewes under high ambient temperature. J. Dairy Sci. 84, 629–640.

Sevi, A., Albenzio, M., Annicchiarico, G., Caroprese, M., Marino, R., Taibi, L., 2002. Effects of ventilation regimen on the welfare and performance of lactating ewes in summer. J. Anim. Sci. 80, 2349–2361.

Sevi, A., Caroprese, M., 2012. Impact of heat stress on milk production, immunity and udder health in sheep: A critical review. Small Rumin. Res. 107, 1–7. doi:10.1016/j.smallrumres.2012.07.012

Sejian, V., Bhatta, R., Gaughan, J., Malik, P.K., Naqvi, S.M.K., Lal, R., 2017. Adapting sheep production to climate change, Sheep Production Adapting to Climate Change. doi:10.1007/978-981-10-4714-5_1

Sevillano, C. A., H. A. Mulder, H. Rashidi, P. K. Mathur, and E. F. Knol. 2016. Genetic variation for farrowing rate in pigs in response to change in photoperiod and ambient temperature. J. Anim. Sci.94:3185–3197. doi:10.2527/jas2015-9915

Shkolnik, A., Borut, A., Choshniak, J., 1972. Water economy of the Bedouin goat, in: Symp. Zool. Soc. London. pp. 229–242.

Silanikove, N., 1997. Why goats raised on harsh environment perform better than other domesticated animals. Options Mediterr. 34, 185–194.

Silanikove, N., 2000. Effects of heat stress on the welfare of extensively managed domestic ruminants. Livest. Prod. Sci. 67, 1–18. doi:10.1016/S0301-6226(00)00162-7

Srikandakumar, A., Johnson, E.H., Mahgoub, O., 2003. Effect of heat stress on respiratory rate, rectal temperature and blood chemistry in Omani and Australian Merino sheep. Small Rumin. Res. 49, 193–198. doi:10.1016/S0921-4488(03)00097-X

Taylor, R.E., 1992. Adaptation to the environment In: Scientific Farm Animal Production. Macmillan Publishing Company, New York.

Van Dijk, J., Sargison, N.D., Kenyon F., Skuce, P.J. (2010) Climate change and infectious disease: helminthological challenges to farmed ruminants in temperature regions. Animal 4:3, 377-392.

West, J.W., 2003. Effects of heat-stress on production in dairy cattle. J. Dairy Sci. 86, 2131–2144.

Zumbach, B., I. Misztal, S. Tsuruta, J. P. Sanchez, M. Azain, W. Herring, J. Holl, T. Long and M. Culbertson. 2008. Genetic components of heat stress in finishing pigs: Development of a heat load function. J. Anim. Sci. 86:2082-2088. doi: 10.2527/jas.2007-0523

5 Appendix

Table A1 – Studies reporting DMI decrease for dairy sheep and goats under heat stress.

Reference	System	Breed	THIrange	DMI loss (kg/d)	DMI (kg DM/d)
Abdalla et al., 1993	Dairy sheep	Finn x Dorset x Rambouillet	19-32	29%	1.9-2.7
Bernabucci et al., 2009	Dairy sheep	Sardinian	19-30	4%	0.8-0.9
Brasil et al., 2000	Dairy goat	Alpine	22-32	8%	1.2-1.3
Brown et al., 1988	Dairy goat	Alpine	19-29	6%	2.5-2.7
Hamzaoui et al., 2014	Dairy goats	Murciano-granadina	19-33	29-35%	1.5-2.5
Hamzaoui et al., 2013	Dairy goats	Murciano-granadina	19-33	21%	1.6-2.0
Leibovich et al., 2011	Dairy sheep	Assaf	26-29	10%	2.5-2.8
Sano et al., 1985	Dairy goat	Saanen	19-33	18%	1.2-1.5

Table A2 – Studies reporting DMI decrease for meat sheep and goats under heat stress.

Reference	System	Breed	THIrange	DMI loss (kg/d)	DMI (kg DM/d)
Alhidary et al., 2012	Meat sheep	Merino	22-32	23%	0.8-1.0
Bhattacharya et al., 1974	Meat sheep	Awassi	19-33	4%	0.5-0.8
Denek et al.,2006 (1)	Meat sheep	Awassi	11-27	17%	1.1-1.4
Denek et al.,2006 (2)	Meat sheep	Awassi	11-27	2%	1.6-1.7
Dixon et al., 1999	Meat sheep	Merino x Border Leicester	15-34	7-12%	1.0-1.2
Indu et al., 2014	Meat sheep	Malpura	32-36	20%	0.8-1.0

Table A3 – Overview of small ruminants studies analysed reporting milk losses under heat stress conditions. The reported results have been converted into FCPM according to Pulina, Macciotta and Nuda (2004) and THI has been normalised based on Marai et al., 2007

Reference	System	THImax	Milk loss (%)	Fat (%)	Protein (%)	FPCM loss (%)
Abdalla et al., 1993	Dairy sheep	32	10%	8-10	4.1-4.8	27%
Brasil et al., 2000	Dairy goat	32	5%	3.3-3.4	2.8-3.0	8%
Brown et al., 1988	Dairy goat	29	13%	3.2-3.4	3.0-3.1	14%
Finocchiaro et al., 2005	Dairy sheep	32	31%	6.0-6.1	5.5-5.6	31%
Hamzaoui et al., 2014	Dairy goat	33	8%	3.8-4.3	3.3-3.7	16%
Hamzaoui et al., 2014	Dairy goat	33	5%	3.6-4.0	2.8-3.4	11%
Hamzaoui et al., 2014	Dairy goat	33	4%	3.8-4.4	3.1-3.6	13%
Hamzaoui et al., 2013	Dairy goat	33	2%	4.2	3.4-3.8	5%
Leibovich et al., 2011	Dairy sheep	29	7%	5.0-5.6	4.9-5.0	12%
Menéndez-Buxadera et al., 2013	Dairy goat	32	9%	5.5	3.5	9%
Menéndez-Buxadera et al., 2013	Dairy goat	32	30%	4.3-4.4	3.3-3.4	29%
Menéndez-Buxadera et al., 2012	Dairy goat	32	3%	5.0-5.4	3.6	7%
Menéndez-Buxadera et al., 2012	Dairy goat	32	3%	4.2-4.6	3.4-3.7	8%
Peana et al., 2007	Dairy sheep	32	19%	6.7	5.8	19%
Ramón et al., 2016	Dairy sheep	30	0%	6.4-6.7	5.4-5.6	1%
Romero et al., 2008	Dairy goat	33	8%	4.4-4.9	3.5-3.7	13%

Table A4 - Diseases affecting small ruminant systems whose incidence or distribution may be affected by climate change (next page)

DISEASE	TYPE	TRANSMISSION PATHWAY	Name	CURRENT EXITS¿? Since	RISK OF EFFECTS OF C.C.	HOW WOULD BE¿?	CONSEQUENCES FOR LIVESTOCK MANAGEMENT	SPECIES AFFECTED MAINLY	SYSTEM AFFECTED MAINLY	REFERENCE
Anaplasmosis	Viral infection	Vector	Tick	Yes	Yes	Expansion tick		Sheep	Anyone	Mysterudetal (2018)
Blue tongue	Viral infection	Vector	Adult culicoides	Yes	Yes	Space spreading		Sheep mainly	Anyone	Ganter (2015); Purse et al (2005)
Brucellosis	Bacterial infection	Direct	*Brucella melitensis*	Yes	Yes	Disease expansion		Sheep Goat	Anyone	Ganter (2015)
Caprine Arthritis and Encephalitis	Viral infection	Direct	(CAEV) Lentivirus (Retroviridae)	Yes	?	-	Prevention of vertical/horizontal transmission	Goat (Sheep)	Anyone	
Contagious Agalactia	Bacterial infection	Direct	*Mycoplasma agalactiae* *M mycoides capri*	Yes	-	-		Goat (Sheep)	Anyone	
Crimean Congo Fever	Virus infection	Vector	Tick Ixodidae Hyalomura	Yes	Yes	Space spreading	Vaccines¿?	Sheep Goat	Anyone	Doc FAO
Foot & Mouth (Aftosa fever)	Virus infection	Direct contact with infected animals	Aphthovirus	No in UE UK (2001)	Yes	Live animals		Sheep Goat	Anyone	Vloet et al (2017)
Lameness	Bacterial infection	Direct	D nodosus F necrophorum	Yes	?	Environemntal conditions (e.g. soil moisture, temperature)		Sheep Goat	All	Green et al (2008); Angell et al (2018)
Listeriosis	Bacterial infection	Feedstuff	*Listeria monocytogenes*	Yes	?	Food		Sheep Goat	Anyone	

Liver fluke	Parasitic infection	Parasite	Helminth Nematodes (*Fasciola hepatica*)	Yes	Yes	Change of parasite lifecycle	Changes in grazing calendar, etc	Sheep	Grazing systems	van Dijk et al (2009) Fox et al (2015) McMahon (2016)
Mastitis	Bacterial infection	Direct	Staphylococcus aureus (Streptococci, coliforms, staphylococci)	Yes	?		Antibiotics treatment	Sheep Goat	All (Intensive systems)	
Parasitic gastroenteritis	Parasitic infection	Parasite	Nematode *Teladorsagia* *circumcincta*	Yes	Yes	Changes of parasite epidemiolgy	Changes in grazing calendar. Treatment	Sheep Goat	Grazing systems	McMahon (2012); Ptochos et al (2016)
Paratuberculosis	Bacterial infection	Direct	*M avium paratuberculosis* (MAP)	Yes	?					
Progressive pneumonia	Viral infection		Lentivirus (Retroviridae)	Yes	?					
Rift valley fever	Viral infection	Vector	mosquito gender Aedes, Culex, Tabanús	Yes	Yes	Change of vector lifecycle	Vaccines¿? Mandatory¿?	Sheep Goat	Anyone	Ganter (2015)
Schmallenberg virus (SBV)	Viral infection	Vector	Culicoide mosquito	Yes. 2011	Yes	New disease. Change of vector lifecycle, and distribution	Vaccines¿? Mandatory¿?	Sheep Goat	Anyone	
Scrapie	Transmissible spongiform	Direct	Prion	Yes	?		None	Sheep Goat	Anyone	Foster et al (2001)

	encephalopathies (TSEs)								
Sheep and goat pox (SGP)	Viral infection	Direct contact Dipteran	Direct contact Diptero *Stomoxys calcitrans*	Only in Greece	Yes	Virus spreading	Sheep Goat	Anyone	Babiuk et al 2008
Tuberculosis	Baterial infection	Direct	*M. bovis*	Yes	?		Sheep Goat		

Table A5. Modelling approaches described in literature for predicting animal disease evolution linked to changes on environmental conditions

Source	Disease	Factor studied and relationship with disease	Region
(Fox et al., 2011)	F.hepatica	To calculate *F. hepatica* infection risk, the Ollerenshaw index was used, with some slight modifications due to the availability of climate data. This model is dependent on the interactions between rainfall and temperature, with the monthly fasciolosis risk value (Mt) calculated as below [23]: $$Mt = n\left(\frac{R}{25.4} - \frac{P}{25.4} + 5\right)$$ Mt = Fasciolosis risk value, n = Number of rain days per month, R = Rainfall (mm/month) P = Potential evapotranspiration (mm/month). For the calculation of potential evapotranspiration (P), the Hargreaves equation for evapotranspiration was used, where Ra is extraterrestrial radiation [MJ m^{-2} day^{-1}] [27,28]: $$P = 0.0023 \times 0.408 \times R_a\left(\frac{T_{max} + T_{min}}{2} + 17.8\right)\sqrt{T_{max} - T_{min}}$$	England
(Blagrove et al., 2017)	Interplay between the optimal climates for vector and virus for human diseases West Nile virus (WNV), chikungunya virus (CHIKV)	Calculation of the Optimal Mosquito Season (OMS): the four-month period of the year in each sub-country when adult vectors are most likely to be active, based on temperature and rainfall data. The green area represents all single vector sub-countries, whilst the red area represents the density of subcountries in which the relevant virus was also found	Global, per country

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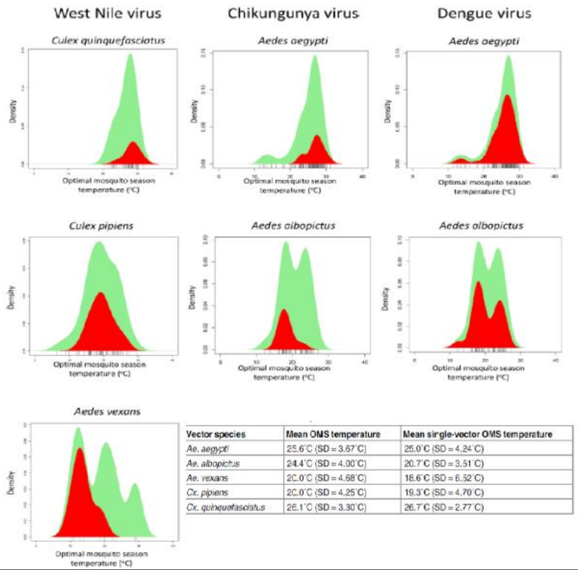
<tr><td></td><td>and dengue virus (DENV)</td><td>

<table>
<tr><th>Vector species</th><th>Mean OMS temperature</th><th>Mean single-vector OMS temperature</th></tr>
<tr><td>Ae. aegypti</td><td>25.6°C (SD = 3.67°C)</td><td>25.0°C (SD = 4.24°C)</td></tr>
<tr><td>Ae. albopictus</td><td>24.4°C (SD = 4.00°C)</td><td>20.7°C (SD = 3.51°C)</td></tr>
<tr><td>Ae. vexans</td><td>20.0°C (SD = 4.68°C)</td><td>18.6°C (SD = 6.52°C)</td></tr>
<tr><td>Cx. pipiens</td><td>20.0°C (SD = 4.25°C)</td><td>19.3°C (SD = 4.70°C)</td></tr>
<tr><td>Cx. quinquefasciatus</td><td>26.1°C (SD = 3.30°C)</td><td>26.7°C (SD = 2.77°C)</td></tr>
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<tr><td>(Purse et al., 2005)</td><td>Blue tongue virus through Culicoides</td><td>it is likely that increases in temperature (particularly at night-time and in winter), as well as increases in precipitation (particularly in summer/autumn) will lead to an increased geographical and seasonal incidence of BTV
transmission by increasing the range, abundance and seasonal activity of vectors. More frequent extreme weather events (particularly winds) could increase vector dispersal, thereby aiding colonization events and leading to disease outbreaks in new areas. Although temperature is an important eterminant of the distributional limits of BTV and its vectors in cooler regions (for example, northern Iberia[82]), which are generally wet enough to support larval development, moisture levels limit vector abundance in warmer areas.</td><td>Europe</td></tr>
<tr><td>(Wittmann et al., 2002)</td><td>Culicoides sonorensis as a vector of African Horse Sickness Virus, BlueTongueVirus and Epizootic Haemorrhagic dDisease of deer Virus</td><td>Table 4. Estimated minimum and optimum temperatures for transmission of different orbivirus serotypes by C. sonorensis. See Table 1 for an explanation of the serotype abbreviations.
<table>
<tr><th></th><th>Temperature (°C)</th><th></th></tr>
<tr><th>Serotype</th><th>Minimum</th><th>Optimum</th></tr>
<tr><td>AHSV4</td><td>9.7–15</td><td>28–30</td></tr>
<tr><td>BTV10</td><td>9.2–15</td><td>27–28</td></tr>
<tr><td>BTV16</td><td>12.6–15</td><td>27</td></tr>
<tr><td>EHDV1</td><td>17</td><td>27–30</td></tr>
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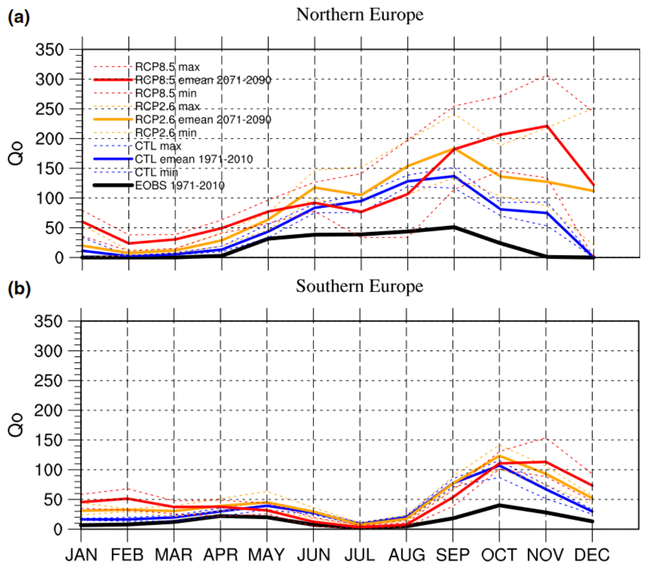
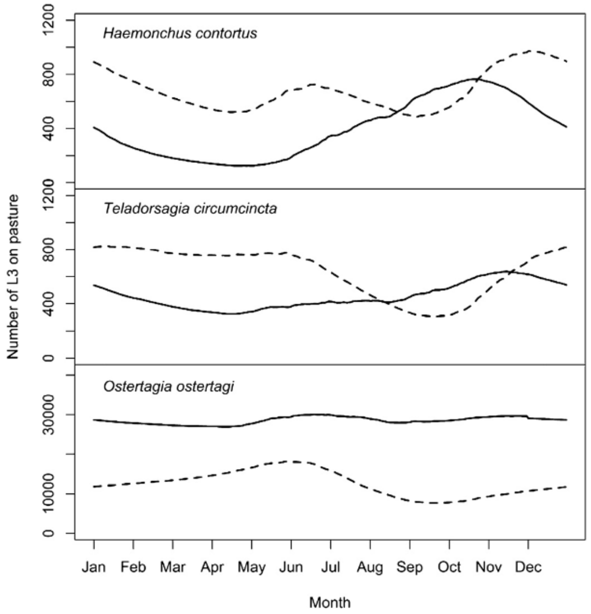
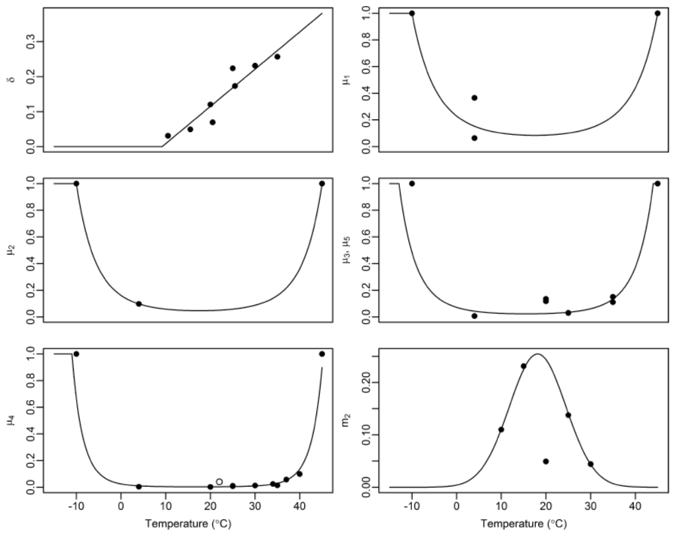
(Rose et al., 2016)	Ovine haemonchosis caused by the nematode Haemonchus contortus (provides model equations and parameters)	A model of the basic reproductive quotient of macroparasites, Q_0 including interactions with regional stocking rate.  	Europe
(Rose et al., 2015)	Gastrointestinal nematode parasites for ruminants using GLOWORM-F (provides model equations and parameters)	Fig1.Predicted number of third stage infective Larvae (L3) on pasture (soil and herbage combined) when using historical climatic data for the period 1969–1999 (solid line) and climatic data based on the **RCP8.5** high emissions climate	South West England

		change scenario for the period 2070–2100 **(broken line)**.  Fig2. Example of temperature-dependent life-history parameters for H. contortus (lines) based on analysis of data in the literature(closedcircles). δ Development rate from egg to L3. µ1 Egg mortality rate µ2 first and second stage larvae mortality rate µ 3 L3 mortality rate in faeces µ 4 L3 mortality rate in soil µ 5 L3 mortality rate on herbage Instantaneous daily rate m1 Horizontal migration (translation) ofL3onto pasture m2 Proportion of total pasture L3on herbage.	

			
(Bennema et al., 2010)	Management factors associated with nematode exposure in dairy cattle	(ODR: optical density ratios of O. ostertagi antibodies)	Belgium, Germany, Sweden, Ireland, UK

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<tr><th>Variable</th><th>Association</th><th>Country[a]</th></tr>
<tr><td>General</td><td></td><td></td></tr>
<tr><td>Type</td><td>Mixed herds have higher ODRs than dairy herds</td><td>B[c]</td></tr>
<tr><td>Size</td><td>The smaller the herd, the larger the ODR</td><td>B[c]</td></tr>
<tr><td>Cows</td><td></td><td></td></tr>
<tr><td>Exposure to pasture</td><td>ODR decreases when exposure to pastures decreases</td><td>B[c], G, I</td></tr>
<tr><td>Grazing time</td><td>The more time the cows spend grazing, the higher the ODR</td><td>B[b], S, UK</td></tr>
<tr><td>Deworming</td><td>ODR deworming when problems > no deworming > preventive deworming</td><td>B[d], G, UK</td></tr>
<tr><td>Grass proportion in diet</td><td>The more grass proportion in the diet, the higher the ODR</td><td>B[b], G, UK</td></tr>
<tr><td>Housing</td><td>The later the cows are housed, the higher the ODR</td><td>B[b], UK</td></tr>
<tr><td>Stocking rate</td><td>The higher the stocking rate the lower the ODR</td><td>B[d], UK</td></tr>
<tr><td>Mowing</td><td>Mowing (partly/all) gives a lower ODR than no mowing</td><td>B[b]</td></tr>
<tr><td>Turn out</td><td>The earlier the cows are turned out, the higher the ODR</td><td>B[c]</td></tr>
<tr><td>Heifers</td><td></td><td></td></tr>
<tr><td>Mowing</td><td>Mowing of all or most pastures → lower ODR than no mowing</td><td>B[d], S, I</td></tr>
<tr><td>Exposure to pasture</td><td>Total confinement and small grassed paddock cause lower ODR than grazing on pasture</td><td>B[d], G</td></tr>
<tr><td>Grass proportion in diet</td><td>Equal or less than 50% lower ODR than no grazing on pasture; no grazing lower than grass only and equal to or less than 50%</td><td>B[b], G</td></tr>
<tr><td>Stocking rate</td><td>The higher the stocking rate the lower the ODR</td><td>B[c], G</td></tr>
<tr><td>Turn out</td><td>The earlier the heifers are turned out, the higher the ODR</td><td>B[c]</td></tr>
<tr><td>Housing</td><td>The later the heifers are stabled, the higher the ODR</td><td>B[c]</td></tr>
<tr><td>Grazing time</td><td>Higher ODR in herds where heifers graze day and night versus herds where they graze <6 h</td><td>B[c]</td></tr>
<tr><td>Deworming</td><td>ODR of herds deworming when problems > preventive deworming</td><td>B[c]</td></tr>
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[a] B = Belgium, G = Germany, S = Sweden, I = Republic of Ireland and UK = United Kingdom.
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<td>(Kraemer et al., 2015)</td>
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Relative contribution of environmental covariates predicting the global distribution of Ae. aegypti and Ae. albopictus
https://doi.org/10.7554/eLife.08347.011
<table>
<tr><th></th><th>Mean contribution Ae. aegypti (%)</th><th>95% confidence interval Ae. aegypti (%)</th><th>Mean contribution Ae. albopictus (%)</th><th>95% confidence interval Ae. albopictus (%)</th></tr>
<tr><td>Temperature suitability</td><td>54.9</td><td>53.7-56</td><td>44.3</td><td>42.7-45.6</td></tr>
<tr><td>Maximum precipitation</td><td>13.6</td><td>12.6-14.6</td><td>13.9</td><td>12.7-14.9</td></tr>
<tr><td>Enhanced vegetation index(mean)</td><td>12.1</td><td>11.3-12.9</td><td>15.3</td><td>14.5-16.3</td></tr>
<tr><td>Minimum precipitation</td><td>9.1</td><td>8.5-10</td><td>16.1</td><td>15.2-16.9</td></tr>
<tr><td>Enhanced vegetation index (range)</td><td>8.3</td><td>7.7-9</td><td>9.1</td><td>8.3-10.1</td></tr>
<tr><td>Urbanicity</td><td>2</td><td>1.3-2.4</td><td>1.1</td><td>0.7-1.7</td></tr>
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<td>(Purse et al., 2017)</td>
<td>Environmental predictors of the recent past</td>
<td>Percentage contribution of top ten ranked predictors to models of cutaneous leishmaniasis where different sets of predictors were considered (averaged across 20 sub-models).</td>
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<tr>
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<td>distribution of leishmaniases</td>
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<table>
<tr><th colspan="3">Abiotic predictors only</th><th colspan="3">Abiotic predictors and all mammal richness</th></tr>
<tr><th>Predictor</th><th>mean</th><th>sd</th><th>Predictor</th><th>mean</th><th>sd</th></tr>
<tr><td>temperature seasonality(bio4)</td><td>31.4</td><td>2.3</td><td>richness (all mammals)</td><td>23.0</td><td>2.9</td></tr>
<tr><td>precipitation seasonality(bio15)</td><td>10.4</td><td>1.5</td><td>temperature seasonality(bio4)</td><td>17.2</td><td>2.0</td></tr>
<tr><td>elevation</td><td>8.1</td><td>1.0</td><td>precipitation seasonality(bio15)</td><td>7.4</td><td>1.0</td></tr>
<tr><td>precipitation driest quarter (bio17)</td><td>6.6</td><td>1.4</td><td>elevation</td><td>6.4</td><td>1.0</td></tr>
<tr><td>temperature annual mean (bio1)</td><td>5.8</td><td>0.7</td><td>max. temp. warmest month (bio5)</td><td>6.0</td><td>1.0</td></tr>
<tr><td>precipitation annual mean (bio12)</td><td>5.7</td><td>0.8</td><td>temperature annual mean (bio1)</td><td>5.2</td><td>0.7</td></tr>
<tr><td>max. temp. warmest month (bio5)</td><td>4.9</td><td>0.9</td><td>precipitation driest quarter (bio17)</td><td>4.8</td><td>0.9</td></tr>
<tr><td>grazed grassland cover</td><td>4.0</td><td>0.6</td><td>precipitation annual mean (bio12)</td><td>4.6</td><td>0.6</td></tr>
<tr><td>cropland foodperennial</td><td>3.5</td><td>0.9</td><td>grazed grassland cover</td><td>4.0</td><td>0.7</td></tr>
<tr><td>Irrigated land area</td><td>3.0</td><td>0.6</td><td>cropland foodperennial</td><td>2.7</td><td>0.7</td></tr>
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