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Innovation for Sustainable
Sheep and Goat
Production in Europe

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Abstract

Climate change is a major threat to the sustainability of livestock production systems globally. Europe and the northern hemisphere are warming at faster pace than the global average and there is little doubt that climate change will have a large impact on livestock performance in Europe unless adaptation strategies are implemented across the whole food supply chain. Small ruminant production systems in Europe are subject to specific challenges regarding their future. On one hand, they could be particularly vulnerable to climate change and other global environmental changes, since a large share of the production is held in marginal areas or/and under semi-arid conditions, which, generally, are within economically disadvantaged areas. Yet on the other hand, small ruminants have features (body size, heat tolerance) that provide competitive advantages against other livestock species in the face of a changing climate. In this deliverable, we report a literature review carried out to shed light on the main impacts that climate change is expected to have on small ruminant production systems in Europe. Additionally, we have come up with specific measures that can help adapt the different type of relevant production systems (e.g. intensive *vs* extensive; pasture based *vs* fully housed; sheep *vs* goat, meat *vs* meat, etc…) to the expected changes in climate across different bio-climatic areas in Europe. A separation between those impacts at the animal level (direct impacts on productivity, fertility, health and welfare) and at the forage level (changes in quantity and quality) allows us to gain a better understanding of the main stressors that are/will be affecting at the component level (animal or forage). For different areas in Europe we have indicated climate change expected impacts and potential adaptation measures tailored for.

As a result of the review, we can anticipate that impacts will be very unequal amongst different bio-climatic regions, countries and production systems. Meanwhile, the successful implementation of adaptation measures will be, although in some cases dependent on factors that are intrinsic to the production system, in most cases modulated by future socio-economic scenarios. In order to formally predict impacts of, and adaptation measures to, climate change at the farm level, some of the information extracted in this report will be numerically grouped to produce different modelling approaches that can help us simulate the effect of changing weather conditions on forage and animal productivity (e.g. due to heat stress) in tasks 3.2 and

3.3., respectively. Such modelling approaches are expected to be integrated into the farm model that is being developed in WP4.

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1 Introduction

The climate in Europe is changing, with higher temperatures and more variable volume and annual distribution of precipitation. These changes are influencing, sometimes dramatically, other abiotic variables including higher likelihood and intensity of fires and floods and changes in nutrient cycles and wind speeds. Such changes will inevitably impact on small ruminant farming – both on the animals directly and the production system more widely.

Small ruminant farming is widespread across Europe, with the highest populations concentrated in the Mediterranean countries, the United Kingdom and Romania (Figure 1). Impacts to small ruminant farming from climate change will therefore likewise extend across Europe, with the biggest impacts coinciding with highest populations. Impacts will be focused in these areas because it is here that small ruminant farming has the largest economic, social and environmental role.

Whilst its absolute significance varies by geographic location, the contributions of small ruminant farming to Europe are extensive and valuable. At a European level, economic contributions are numerically relatively small. In 2010, there were 9 599k LSU of sheep and 1 231k LSU of goats in the EU-28 – c.8% of the total livestock kept. This is in comparison to 64 045k LSU of cattle, 37 076k LSU of pigs and 20 332k LSU of poultry. Sheep and goat meat represented 1.7% of the total EU-28 meat output by weight in 2014, whilst 3.2% of milk and milk products came from sheep, goats and buffalo (Eurostat, 2015).

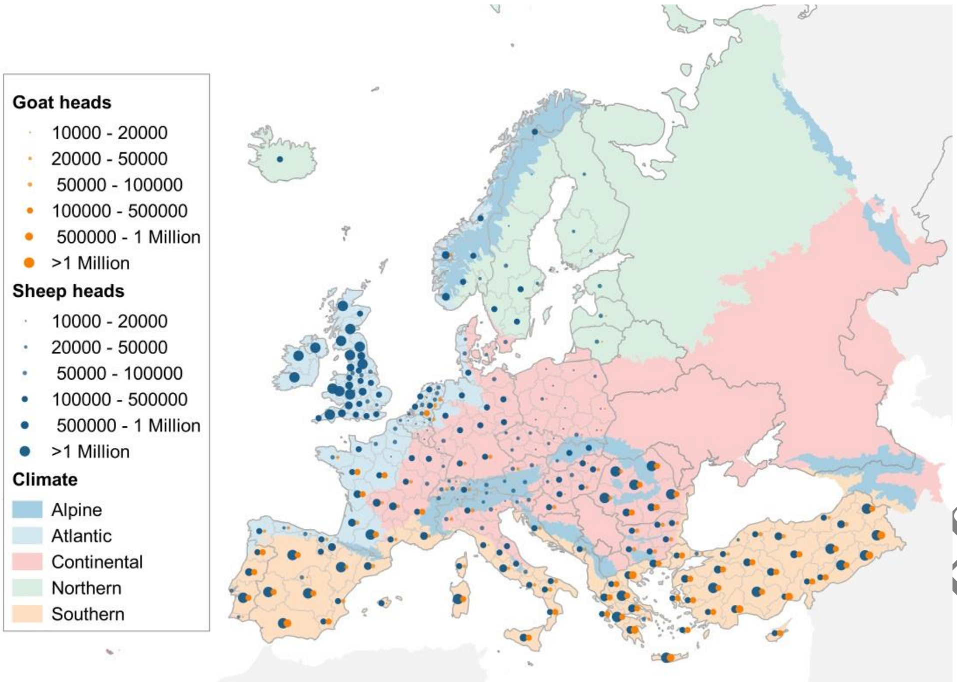

Figure 1 - Distribution of small ruminant livestock in Europe (Eurostat, 2015)

This economic contribution of small ruminants, however, varies by country and in some places is substantial. In 2010, sheep comprised 23% of total UK livestock (by livestock units), whilst in Greece, sheep are the most dominant livestock category (Eurostat, 2015). Sheep and goats together account for 56% (38% sheep, 18% goats) of the total livestock in Greece (Marquer et al., 2015) and, together with buffalo, are responsible for 52% of the country's milk production (Eurostat, 2015) and 20% of its meat production (Marquer et al., 2015).

Aside from economic values, small ruminants' environmental contribution through maintenance of grasslands and to social wellbeing is valuable. Sheep and goats can convert low quality forage into high quality livestock products. Therefore, in marginal areas and less productive agricultural land they are often the only source of agricultural income. Additionally, sheep and goats can graze in hard to reach areas to arrest succession of grasslands to scrub and woodland and such grazing helps retain landscape diversity. The social and environmental contributions of small ruminants in Europe are therefore valuable to long term sustainability of agriculture.

Despite this value, across most of Europe small ruminant numbers have shown recent decline, with total numbers in Europe falling by 5% for sheep and 10% for goats in the last decade.

Between 2005 and 2014, Spain and Portugal's sheep numbers declined by around a third, while in Ireland, Germany, France and the Netherlands sheep numbers declined by about a fifth (Marquer et al., 2015). In the UK, sheep numbers declined slightly over the last decade (-4%) but the total number of sheep and lambs increased by 7.2% between 2010 and 2015. Sheep populations in December 2015 indicate continued growth for overall UK sheep numbers, with the breeding flock remaining stable (DEFRA, 2016). In Eastern Europe, meanwhile, sheep numbers have increased by around 30% since 2005 (Eurostat, 2015).

The contribution of climate change on shaping small ruminant farming in Europe is expected to increase. As with all agriculture, small ruminants are affected by the wider environment, whether through direct effects of climate on animals, or indirect effects via pasture, forage, feed crops or parasites and pathogens. To understand the specific repercussions climate change could have for small ruminant production in different areas of Europe and how the sector could react to adapt to, exploit or mitigate these, we here conduct a review of the best to-date information available on climate change interactions and weather effects on sheep and goat systems. Sources investigated include EU-funded projects, the EU FACCE JPI MACSUR Knowledge Hub: http://macsur.eu/ (e.g. Dono et al., 2016 ; Kipling et al., 2016; Vitali et al., 2016; Rezaei et al., 2015; Kochy et al., 2015; Kässi et al .,2014; Lehtonen et al., 2014; Höglind et al. 2013), modelling studies (e.g. EPIC model: Dono et al., 2016; PASIM model: Bellochi et al., 2014), site-specific data from project partners and more general academic and white literature and climate simulations. Of particular interest we reviewed information from 5 recently finished EU-funded FP7 projects relevant to the issues in relation with climate change effects on small ruminant production systems: (ANIMALCHANGE: http://www.animalchange.eu/, MULTISWARD: https://www.multisward.eu/, SOLID: http://www.solidairy.eu/ and LegumeFutures: http://www.legumefutures.de/). The specific outputs from ANIMALCHANGE that we were interested were those providing analysis on impacts and vulnerability of livestock to climate change (this includes climate variability) and those in relation with potential adaptation measures to cope with climate change in Europe (e.g. Hofer et al., 2016; Chang et al., 2015; Hoekstra et al. 2015; Dumont et al., 2014; Lüscher et al., 2014ab). From Multisward project (Peyraud et al., 2014) we were particularly interested in those aspects in relation with the role of multifunctional grasslands (i.e. through enhanced grass species diversity: e.g. Finn et al., 2013) as a strategy for more adaptive and resilient grassland-based small ruminant systems to climate change (e.g. Husse et al., 2016). For SOLID we were particularly interested in looking at the adaptive capacity of different animal breeds may adapt to organic low input systems to enable improved productivity, product quality and health and welfare. We were also very interested in those studies analysing the role of alternative forages and agro-industry by-products as an adaptive response to cope with scarcity-climate change driven of conventional forages (e. g. Pardo et al., 2016; Rinne et al. 2012). LegumeFutures´s main interesting objectives for this review included the role of important protein-rich crops and forage crops (e.g. clover and alfalfa) produced in Europe as diet protein feed for a potential protein-constrained future. Also, we reviewed the role of enhancing legumes in small ruminant systems as an adaptive strategic tool for climate change adaptation (Murphy-Bokern et al., 2014).

The review first identifies the climatic changes predicted across Europe, dividing the continent into the five geographic/ecological zones identified by the IPCC (Kovats et al., 2014) and based on the climate zones of Metzger et al. (2005). It then assesses possible indirect impacts of these changes on sheep and goats via 1) forage quality and quantity and 2) pasture/grassland areas used by grazing animals; and 3) the possible direct effects of the changes on animal productivity and welfare. Figure 2 summarises these direct and indirect effects of climate change on small ruminant production systems. The review finishes by identifying some of the adaptation measures tested at field and animal level to alleviate some of the identified threats. These measures include the role of grass biodiversity in building pasture resilience against climate change.

This review is written as part of the Horizon 2020 research project Innovation for Sustainable Sheep and Goat Production in Europe (iSAGE), which brings together 33 industry and research institutions across seven European countries to review, assess and demonstrate sustainable sheep and goat production across Europe. By identifying the ongoing and predicted future changes in climate across Europe and the interaction of these with small ruminant production, this review will contribute to these project goals by establishing potential threats and opportunities the sector faces in the imminent and longer term future. In doing so, it provides an opportunity for research, planning and implementation of practices and technologies at a farm level, and for recognition of shifts in sectoral structure at an industry level, that could help combat/exploit the impacts foreseen. The review makes further steps to facilitate this by providing context-specific examples of adaptations already tested at field and animal level.

The data extracted in this review will feed forwards into the development of semi-empirical meta-models that relate the effect of weather and site conditions and different adaptation measures to pasture production (Task 3.2) and the subsequent consequences for sheep and goat performance (Task 3.3), These models will be incorporated in a new whole-farm model to be developed in WP4 and assist with the identification of appropriate innovative solutions in WP5.

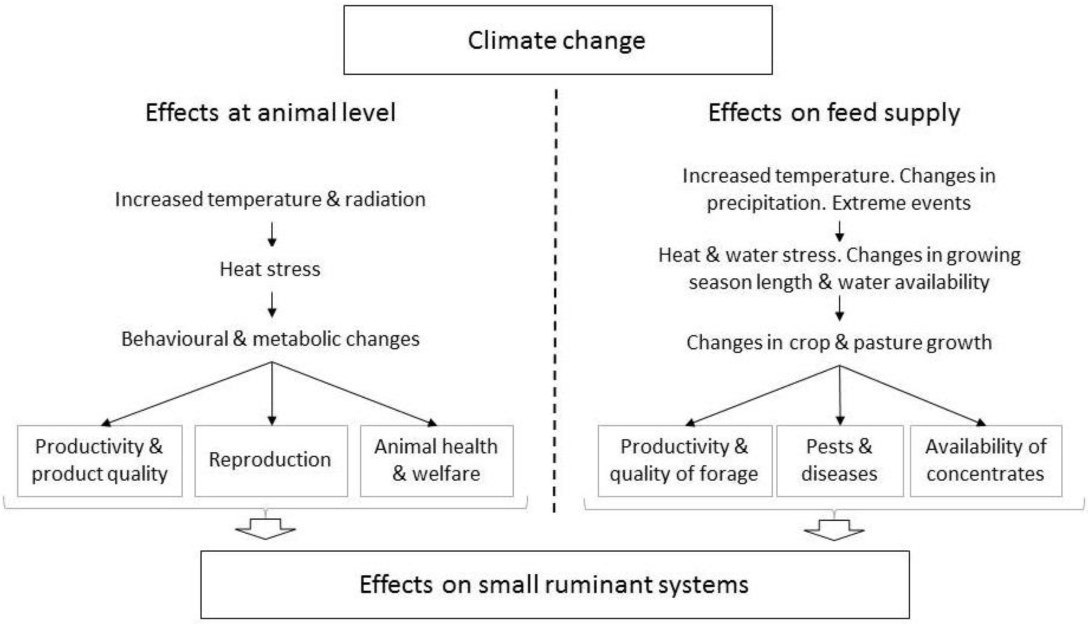

Figure 2 – Diagram of possible effects of climate change on small ruminants production systems.

2 Climate change projections in Europe

2.1 Temperature

Average temperatures across Europe are tending to increase and all scenarios tested using climate model projections indicate further increase in the next decades (Kovats et al., 2014). Changes, however, will vary in both magnitude and temporal distribution across different regions of Europe. Temperature increase will be highest in winter in Northern and Continental regions and in summer in Southern Europe. Atlantic regions tend to have more warming in autumn and less warming in spring (Goodess et al., 2009; Kjellström et al., 2011). Overall, warming is expected to be greatest in the Northern and Alpine regions: 2.0–4.2°C and 1.9–3.4°C respectively, but will likely reach a minimum 1.4°C everywhere (Jacob et al., 2014). These projected changes in temperature will lengthen growing seasons which will affect plant phenological phases (Schwartz et al., 2006).

These projected changes of temperature (and other climate indices) for the five sub-regions are summarised in Table 1 and Figure 3. The EURO-CORDEX projections (Figure 3) (Jacob et al., 2014) are similar to projections from the ENSEMBLES project, thus providing confidence in the results.

2.2 Precipitation

Annual precipitation across Europe has also changed in the last decades. Precipitation in Northern Europe has increased by up to 70mm per decade and in Southern Europe decreased by up to 90mm per decade since 1950 (EEA, 2012, based on Haylock et al., 2008). These trends are likely to continue in Northern and Southern Europe, but in other European regions forecast changes are less clear. An overall increase in these regions, is however, expected (Table 1, Figure 3) (Kjellström et al., 2011; Jacob et al., 2014). Temporally, summer rainfall is expected to decrease everywhere except the Northern region, while winter rainfall is generally expected to increase, with the exception of the Southern region where no consistent results have been found (Christensen et al., 2013; Ciscar et al., 2014; Kovats et al., 2014).

Across the whole of Europe, rainfall will become more sporadic and heavy rain events may increase substantially in most areas and seasons (European Environmental Agency, 2015; Jacob et al., 2014; Kovats et al., 2014; Madsen et al., 2014). Dry spells will also become longer (although less frequent) in Central regions and especially in Southern Europe, where more frequent and longer droughts are additionally expected (Forzieri et al., 2013; Jacob et al., 2014). Even in regions where summer precipitation is projected to increase, droughts may become more severe, with warmer temperatures driving higher evapotranspiration rates and reduced soil moisture (Wong et al., 2011).

2.3 Trends in flood and fire risk

The changes in temperature and precipitation patterns will increase flood risk and extent. Droughts that harden the soil and reduce permeability (Howard, 2013) and heavier precipitation events that increase the probability of soil and stream saturation will act in synergy to exacerbate flooding and increased frequency and intensity of flooding is therefore expected in most regions across Europe. Flooding is not expected to increase in north and north-eastern Europe, however, where warmer winters mean less precipitation falls as snow, reducing snow melt and decreasing chance of spring flooding (Rojas et al., 2012; Madsen et al., 2014; European Environmental Agency, 2016).

Changes in temperature and precipitation will also increase fire risk. Fires start when it is dry and warm and there is sufficient vegetation to provide fuel. Extended summer droughts are a particular risk factor (Brown et al., 2016). Such conditions are predicted to increase during the summer period across the whole of Europe, except the Northern region. These conditions will also increase in the late spring/early autumn in the Southern, and possibly some of the Continental, regions. In these areas, up to a month’s extension to the fire risk period is possible (Giannakopoulos et al., 2009).

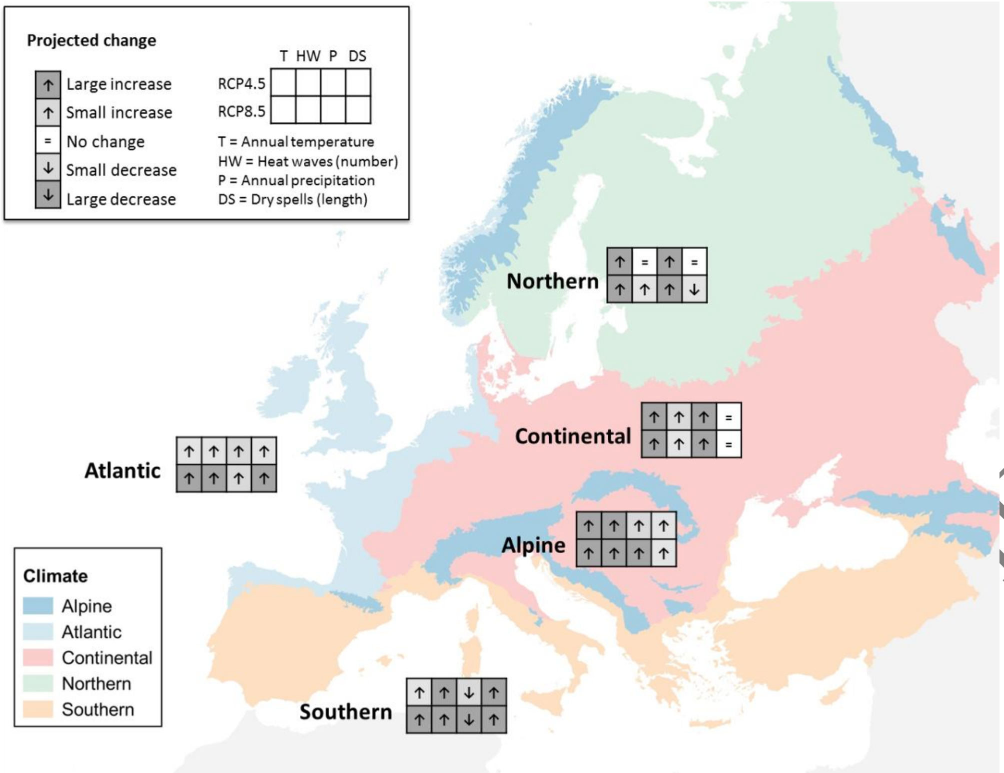

Figure 3 – General trends of several climate variables for European sub-regions. Indices represent changes for 2071-2100 with respect to 1971-2000 based on RCP4.5 and RCP8.5 scenarios (based on Jacob et al, 2014).

Table 1 - General trends of several climate variables and associated risks for European sub-regions. Indices represent changes for 2071-2100 with respect to 1971-2000 based on RCP4.5 and RCP8.5 scenarios (based on Jacob et al., 2014).

	Alpine	Atlantic	Continental	Northern	Southern
Temperature	Increase in mean annual temperature:	Increase in mean annual temperature:	Increase in mean annual temperature:	Increase in mean annual temperature:	Increase in mean annual temperature:
	1.9-3.4 (RCP 4.5)	1.4-2.1 (RCP 4.5)	1.6-3.2 (RCP 4.5)	2.0-4.2 (RCP 4.5)	1.9-2.7 (RCP 4.5)
	3.9-6.0 (RCP 8.5)	2.7-3.6 (RCP 8.5)	3.7-5.2 (RCP 8.5)	4.1-6.2 (RCP 8.5)	3.9-5.4 (RCP 8.5)
	Increase of heat waves	Slight increase of heat waves	Slight increase of heat waves	Slight increase of heat waves	Increase of heat waves
Precipitation	Increase in annual total precipitation	Slight increase in annual total precipitation	Increase in annual total precipitation	Increase in annual total precipitation	Decrease in annual total precipitation
	Heavy rain events increase all seasons	Heavy rain events increase all seasons	Heavy rain events increase all seasons	Heavy rain events increase all seasons	Heavy rain events increase all seasons bar Iberian Peninsula in summer (decrease)
	Dry spells slightly longer in the Pyrenees. Slightly shorter in the Alps and Scandinavia.	Dry spells longer (North Spain, France)			Dry spells substantially longer
Other risks	Slight increase in risk of fires (Pyrenees)	Increased risk and severity of floods (UK).	Increase in risk and severity of floods.	Decrease in risk of spring floods.	Increase in risk of floods linked with heavy rain events.
		Increase in frequency of fires	Slight increase in risk of fires		Substantial increase in frequency of fires

3 Effects of climate change on forage production

One of the most important indirect impacts of climate change on small ruminant systems in Europe is expected to be through changes in feed supply. This change in feed supply will be both quality and quantity. Plant and quality and quantity respond to concentrations of carbon dioxide (CO_2), changes in temperature and rainfall patterns (driven by changes in occurrence of extreme climatic events or changes in average conditions) and stressors such as ozone concentration or salinity. The extent to which these variables can affect forage production will depend on complex interactions between these variables, nutrient availability, type of forage (e.g. C3 *vs* C4 species, annual *vs* perennial, grasses vs forbs vs legume, herbaceous vs woody species), level of ecological interaction (botanically diverse, grazed *vs* mown) and indirect effects of climate change on forage pests and diseases.

3.1 Elevated CO_2

Many studies have confirmed that elevated CO_2 increases plant growth and yields (Ainsworth and Long, 2005; Nowak et al., 2004; Tubiello et al., 2007). This increase is mainly due to photosynthetic stimulation in C3-plants and enhanced water use efficiency (WUE) through stomatal closure. When no other climatic factors are considered, trees and shrubs have the greatest response to elevated CO_2. Legumes tend to have a greater response to elevated CO_2 concentrations than non-fixing grasses (Allard et al., 2003; Nowak et al., 2004), which have a relatively low response (Ainsworth and Long, 2005). For example, in a FACE experiment with CO_2 atmospheric enrichment, Hebeisen et al. (1997) found that white clover yield increased 17% compared with 7% for perennial ryegrass.

On average, the stimulatory effect of doubling the ambient CO_2 on grassland ecosystems increases above ground production by 15-20%. This increase is about half that expected from consideration of the photosynthetic response to CO_2 (Campbell and Stafford Smith, 2000; Nowak et al., 2004). Furthermore, the effect may vary widely (0-30%) depending on the species, system and seasonal conditions, with higher responses expected in dry and warm-season grassland systems (Campbell and Stafford Smith, 2000; Soussana and Lüscher, 2007).

For example, C3 plants have a greater response than C4 plants. In C3-plants, increases in leaf photosynthesis of 0.30-0.50 have been reported when doubling atmospheric CO_2 under optimal conditions (Ainsworth, 2005, Ellsworth et al., 2004). Conversely, contrasting results have been found for C4-species with some studies indicating little effect (Ainsworth and Long, 2005; Leakey et al., 2006) but others reporting increases in biomass yields (Wand et al., 1999; Nowak et al., 2004), although not as much as in C3-species. This is because the photosynthetic pathway of C3 plants is not saturated at current atmospheric CO_2 levels. Therefore, photosynthesis is stimulated when CO_2 increases. In contrast, when there is water, photosynthetic rates of C4 plants are CO_2-saturated at current atmospheric concentrations, thus explaining the negligible response under elevated CO_2.

Despite this constraint, several C4 species still show a positive growth response to increased CO_2, as other factors may be enhanced, such as improved resource-use efficiency (Polley et al., 2003). Elevated CO_2 levels lead to a partial closure of leaf stomata in plants, reducing stomatal conductance to water and thereby decreasing transpiration rates. As a result, water use efficiency increases, and plant productivity under water stress improves, which can be of crucial importance in water-limited grassland ecosystems (Morgan et al., 2004; Leakey et al., 2009; Drake et al., 1997). However, in wet regions there more run-off risk through reduced plant transpiration, resulting in excess water at the land surface (Betts et al., 2007).

However, the extent of the CO_2 fertilisation effect on plant growth and increased biomass production is still not clear (Long et al., 2006; Tubiello et al., 2007; Ziska and Bunce, 2007). This uncertainty is from the many complex interacting processes in the soil-water-plant system that may influence the long-term response of grassland ecosystems to a gradual increase of CO_2 in the atmosphere. Herbage C3 species have greater production responses to high CO_2 when temperatures are high (Long, 1991) until temperatures get too high and stress the plant. For ryegrass dominant pastures, Casella et al. (1996) showed that high levels of CO_2 can enhance herbage accumulation between 14.5 and 18.5 ºC; however above 18.5 ºC, the negative effects of increasing temperature may offset the positive effect of elevated CO_2. Enhanced CO_2 concentrations tend to decrease forage nitrogen (N) content and increase total non-structural carbohydrates (soluble carbohydrates) and starch content, though there does not appear to be any significant effect on forage digestibility (Dumont et al., 2015). The protein content of C3 grasses is expected to decrease in non-leguminous plants (Soussana et al., 1996; Isopp et al., 2000; Myers et al., 2014), although this may be partially counteracted by the expected increase in the legume content of swards (Thornton et al., 2009).

Therefore, the effects of changes in CO_2 on feed supply will vary depending on the region, the plant types and interactions between temperature and water availability. Correspondingly, the indirect effects of CO_2 on sheep and goats will also vary across Europe.

3.2 Temperature

All plant species have critical high and low temperature thresholds for development and growth. The short-term response of photosynthesis to temperature is normally distributed with net photosynthesis increasing until an optimum temperature (generally between 10 and 30ºC) before declining (Larcher, 1969, 2003). However, plants acclimatise their metabolism to medium and long-term temperature changes that have less effect on photosynthesis (Larcher, 1969). Plant growth, however does not only depend on photosynthesis.

Therefore, temperature influence plant growth in other ways, especially when the temperatures nears 0ºC (Körner, 2003). This influence is because growth involves the formation of new plant tissue from cell division and expansion. This division and expansion slows at low temperatures. For C3 species, minimal growth occurs below 6 ºC, with an optimal temperature range for growth between 20-25ºC for cool-temperate species (e.g. perennial ryegrass) and slightly higher (20-28ºC) for warm-temperate species (e.g. cooksfoot). In comparison, C4 species (e.g. maize or paspalum) are better suited for higher temperatures, with optimal ranges between 29 and 35ºC.

However, the overall effect of high temperatures depends on interactions with other climatic factors, especially water availability. Thereby, in mid to high latitudes of Europe and in mountainous regions, increasing temperatures are expected to have a positive effect on plant production (Dumont et al., 2015; Graux et al., 2013; Hopkins and Del Prado, 2007; Watson et al., 1997). Southern Europe by contrast may experience reduced forage production (up to 30% reduction by 2050 in some areas). This reduction will be due to a combination of very high temperatures and reductions in overall precipitation, especially over the warmer months, and increased inter-annual variability (Dumont et al., 2015; Rötter and Höhn, 2015). Further effects may be seen in grain crops due to faster growth and ripening shortening the grain-filling period (Rezaei et al., 2015).

Increased temperatures tend to reduce nutrient availability in plants, particularly N content (Dumont et al., 2015; Hopkins and Del Prado, 2007; Thornton et al., 2009). Some authors have also reported reduced plant digestibility and water soluble carbohydrates and an increase in fibre content in C3 species from increased temperatures (Hopkins and Del Prado, 2007; Thornton et al., 2009), although this is disputed (Dumont et al., 2015) and not recorded in C4 species (Wilson and Ford, 1973).

Therefore, changes in temperature will affect plant growth by affecting cell division and expansion. These effects on plant growth will indirectly effect sheep and goats by altering the amount of feed. These effects vary depending on region and plant type.

3.3 Water availability

Water is a primary requirement for plant growth and development. More water availability, as is predicted for northern Europe, promotes plant growth and increases its quality (Matías et al., 2011; Sardans and Peñuelas, 2013). Conversely, less water availability decreases plant respiration and metabolic activity and decreases productivity. The magnitude of this decrease, however, varies depending on the plant species and the severity and duration of the dry period. In the coming decades, these conditions will become more frequent in Europe, as the length of dry spells is expected to increase, especially in the Southern region (Jacob et al., 2014). Photosynthesis in C4 plants is equally, or even more sensitive to water deficit than C3 plants, despite the greater capacity and water use efficiency of their photosynthetic pathway (Lee et al., 2013).

Rainfall is also projected to become more intense, increasing the risk of flooding in certain areas. This may lead to a temporary excess of soil moisture, decreasing grass productivity (McFarlane et al., 2003). Waterlogged soil after extreme precipitation events decreases net photosynthesis and growth. If waterlogging is high and long enough, the plant will die. Many pasture grasses and legumes survive for just a few days when immersed in water (Woods, 1993). Other potential effects of floods include spread of weeds (Griffiths, 2009), reduced plant energy content (Donath et al., 2004) and in the most severe cases land may require full cultivation and replacement (ADAS, 2014). Summer floods tend to cause more damage than winter floods (Griffiths, 2009; Morris et al., 2010; Morris and Hess, 2008) and very mild flooding can benefit plants from the increased availability of water and nitrate resources (Wright et al., 2015).

However, the ultimate response of grassland ecosystems depends on the interactions and combined effects of all climate variables (e.g. CO_2, temperature, water availability) which will change concurrently. For example, although annual mean precipitation is projected to increase in many regions of Europe, warmer temperatures and longer dry spells could counteract to some extent the positive effect on plant production. This counter is from heat stress and reduced soil moisture due to increased evapotranspiration (Izaurralde et al., 2011). This is in accordance with findings from several ecosystem manipulation experiments in grasslands, simulating different rainfall conditions (Picon-Cochard et al., 2015). Results indicated that climatic water balance (precipitation-potential evapotranspiration) explained variation of grassland biomass across different sites (temperate to semi-arid regions) with higher accuracy than precipitation (Picon-Cochard et al., 2015).

Furthermore, when combined with drought conditions, high temperatures increase the risk of wildfires (particularly in southern Europe). While there is usually a short-term boost in plant quality following burning (Allred et al., 2011; Egan, n.d.), soil N availability decreases over time (Egan, n.d.; Ward, 1995). If soil is burned multiple times it is less fertile in the long term, causing a potential reduction in yields (Nikolov, 2011; Ojima et al., 1994).

Variability in water availability can also constrain the enhanced plant productivity associated with rising atmospheric CO_2 concentration. While experiments in temperate grasslands in France indicated that elevated CO_2 levels may increase drought resistance and recovery by enhancing WUE; in Hungary elevated CO_2 only produced a positive response on biomass production when climatic conditions were less stressful (Picon-Cochard et al., 2015). This is in accordance with a recent review study on temperate C3 grasslands, which has shown that the CO_2 fertilisation effect (CFE) is strongest under average water availability but reduces when it is wetter, drier and/or hotter (Obermeier et al., 2017). Nowak et al. (2004) also found evidence of greater productivity with more CO_2 in drier ecosystems or conditions (Nowak et al., 2004). Based on these results, they suggested that the plant productivity response to increasing CO_2 may peak at some intermediate precipitation regime.

Therefore, water availability will also effect feed productivity and has interactions with CO_2, temperature and soil health.

3.4 Nutrient cycling

While an increase in CO_2 concentration is expected to promote plant growth, sufficient nutrients are required to support this increase. Thereby, managed pastures with a high external input of N have greater productivity when CO_2 increases but little or negligible response has been observed in pastures with low N supply (Nowak et al., 2004). For example, Casella and Soussana (1997) found that doubling CO_2 concentrations increased gross canopy photosynthesis by 33% in perennial ryegrass pastures (C3 plants) under high N fertilisation. With low soil N, the CO_2 stimulation (particularly among non-legumes) is lower (Kimball et al. 2002; Nowak et al., 2004). Therefore, increased biomass production under elevated CO_2 may not be sustained in natural and semi-natural ecosystems due to nutrient limitations (Luo et al., 2004).

Experiments have also shown that elevated CO_2 levels usually lead to reduced N content in forage species (Cotrufo et al., 1998; Dumont et al., 2015) and favour species that fix N_2 (i.e. legumes) over non-fixing species (Grünzweig and Dumbur, 2012; Navas et al., 1997), but it may also increase nutrient uptake capacity by enhancing C3 plants' root growth and mycorrhizal associations (Rillig et al. 1998; Sardans and Peñuelas, 2013; Soussana et al., 1996; Hebeisen et al., 1997; Reich et al., 2001).

However, in the long term N availability may be reduced due to slower decomposition of litter. In addition to lower litter degradability, warming may constrain microbial activity by promoting soil moisture loss, directly or indirectly through enhanced plant growth (Luo et al., 2004). Thereby, the gradual accumulation of N in biomass reduces the availability of soil N and ultimately limits plant growth response to CO_2 or other climate variables (Reich et al., 2006; van Groenigen et al., 2006; Parton et al., 2007).

Precipitation patterns also have an effect on nutrient cycling, with higher rainfall boosting plant nutrient uptake and lower rainfall seeing nutrients remaining in the soil, where they are vulnerable to loss via leaching or erosion (Seddaiu et al, 2016; Matías et al., 2011). Furthermore heavy rainfall events are expected to become more intense and be punctuated by longer dry periods, thus increasing the risk of soil erosion and potentially leading to greater leaching of nutrients from the soil (Del Prado et al., 2014; Hopkins and Del Prado, 2007; Kipling et al., 2016).

The predicted warmer and drier climate in the Mediterranean area will affect soil nutrient cycling and other ecosystem services (Cheddadi et al., 2001). Mediterranean plants already have a characteristically low nutrient content (Sardans and Peñuelas, 2013) and phosphorus is often a limiting factor (Sardans et al., 2006), particularly for legumes (Soussana et al., 2010). Low phosphorus availability is often a problem in soils with low moisture content, and as such is likely to become more of a problem in southern Europe as it becomes drier (Ashraf et al., 2010).

3.5 Diversity in botanical composition

Grasslands are often characterised by pastures that are botanically diverse and changes in climate variables will affect plant species dynamics and composition, with consequences for seasonal patterns of pasture growth and nutritive value. Warming and increasing CO_2 levels are expected to favour legumes over grasses (Hopkins and Del Prado 2007; IFAD, 2012; Trnka et al., 2011); however, legumes will suffer more from increased ozone levels than grasses (ICP Vegetation, 2011). Results from rainfall manipulation experiments in temperate grasslands showed that under moderate drought conditions, multispecies mixtures performed better than monocultures, which was attributed to interactions between legumes and non-legumes leading to better access to water from deeper levels, and less vulnerability to soil N limitations (Picon-Cochard et al., 2015; Hoekstra et al., 2015; Hofer et al., 2017). However, in sites where more extreme drought conditions occurred, this pattern was not observed as growth almost ceased in both, monocultures and mixtures (Picon-Cochard et al., 2015; Hofer et al., 2016). This makes prediction of overall changes in species composition difficult.

The proportion of forbs is also expected to increase, particularly following severe droughts, when grasses may also dominate at the expense of legumes (Dumont et al., 2015; Picon-Cochard et al., 2015). Some studies have found that these changes in species composition following a drought may only last a few years before reverting to their original state (Trnka et al., 2011). Climate change is thus not expected to have a large effect on chemical composition of grass species, but it has been shown to result in changes in the botanical composition of the sward (Dumont et al., 2015).

Elevated atmospheric CO_2 concentration is predicted to enhance C3-species over C4 species. However, C4-species are expected to thrive compared with C3 species (Howden et al., 2008) in the hotter conditions which are projected across Europe (IFAD, 2012; Thornton et al., 2009). In Mediterranean regions in particular, where it will become drier as well as warmer, increased domination of low quality xeric species is predicted (Dibari et al., 2015), with a displacement of grass and dwarf shrub steppes at the expense of existing sclerophyllous shrubland. In these areas, the projected changes in temperature and rainfall patterns may override the potential benefits of increased CO_2 for C3 grasses, but less so for C4 types (Winslow et al. 2003). Climate change will have a major long-term influence on grassland plants whose persistence depends on soil seed banks (Porqueddu et al., 2016). In Mediterranean areas, pasture and forage species survive the dry summer existing as dormant seeds (Ooi, 2012). Ooi et al. (2012) found that whereas mean temperature increase had no effect on seed dormancy, future heat wave conditions produced soil temperatures that significantly increased dormancy loss, especially in seeds from cooler, high elevation populations. Grazing pressure also seems to have an effect on soil seed bank dynamics. Heavy grazing has been shown to be unfavourable to the seed bank of grasses and crucifers annuals and reduce palatable plant species in the seed bank (Sternberg et al., 2003; Koc et al., 2013).

Pasture diversity has also been shown to enhance the elevated CO_2 response compared with monocultures. For example, Reich et al. (2001), under elevated CO_2, found that pastures containing four, nine and sixteen species increased total biomass by 10, 18 22%, respectively compared with a monoculture that increased 7%.

Extreme events may also play a crucial role on the plant community composition of some particular habitats (e.g. Zwicke et al., 2013). For example, in cool climates (e.g. Boreal, Alpine) very-low temperature events are necessary for frost-resistant species, in order to prevent the habitat invasion of competing plants (Körner et al., 2003); while in warm humid areas, an increase in the frequency of dry periods may enhance the development of heat- and drought-tolerant C4 grasses. Risk of wildfires is also projected to increase, particularly in southern Europe, when heat waves are combined with drought conditions. Burned land is more vulnerable to erosion, which leads to a further loss of nutrients (Pausas and Vallejo, 1999). In such conditions, the survival of grassland plants is dependent on the hotness of the burn and the plant species. Some legumes can survive a very hot burn (>250°C), while most grasses cannot (Ward, 1995).

Whilst it is difficult to predict community responses, it seems likely that plant diversity will suffer under climate change. In a study of 1350 European plants, it was predicted that more than half would become vulnerable or threatened by 2080, with the greatest losses occurring in mountainous regions (Thuiller et al., 2005). Diversity is important for pasture resilience to climate change. Communities with high species richness tend to be more resistant to extremes and to have greater recovery potential (Craine et al., 2012; Wright et al., 2015), they have also been found to have greater resistance to weed invasion (Finn et al., 2013). Moreover, mixtures of different species in swards have been demonstrated to produce significant gains in forage DM yield compared with the highest yielding monocultures (e.g. Finn et al., 2013; Kirwan et al., 2007, even at low proportions of legume abundance (Brophy et al., 2017). However, attempts to recreate stable and persistent species mixtures have not always been successful (Revell et al., 2013). Careful pre-selection of the species for use in managed grassland systems has been recommended, paying particular attention to those traits enhancing ecosystem functions, (e.g. biomass production, N yields, weed suppression) but also taking into account competitive abilities relative to each other (Brophy et al., 2017).

Systems with a herbaceous layer dominated by annuals had substantially higher post drought recovery, particularly when grazed (Ruppert et al., 2015), than those with perennial species. This is because they produce and scatter a large quantity of seed in favourable years and the seeds live in the soil for several years (Koc et al., 2013). In Mediterranean areas, drought-tolerant perennial forage species could be very useful in systems where annual species have senesced in late spring (Volaire, 2008). However, very few perennial species can overcome the summer Mediterranean climate. The desired characteristics of these species (e.g. tall fescue) should include dormancy or low growth during summer and high water use efficiency during the growing season (Annicchiarico et al., 2013).

There are both annual and perennial legumes that are suited to Mediterranean conditions. For annual legumes, the most promising ones have been Mediterranean clover and the annual medics. Amongst perennial legumes lucerne is very well known for its tolerance to drought and it is valued in many farming systems for its ability to produce forage over the warmer months (Porqueddu et al., 2016). Still there is a need to breed for more productive cultivars to sustain rainfed lucerne-based farming systems (Latta et al., 2002; Pecetti et al., 2008; Martiniello, 2009; Ovalle et al., 2015). Other interesting perennial legumes, which can escape summer drought through dormancy and later regrow in autumn, are sulla and sainfoin.

3.6 Ozone

Emissions of ozone (O_3) precursors are decreasing in Europe (Tubiello et al., 2007), though European O_3 concentrations are predicted to increase in the future due to emissions in other parts of the world (Fuhrer, 2009). The effect of O3 on pastures is very difficult to estimate, as it depends on plant species, level of diversity, management practices, site conditions, etc. (Fuhrer, 2009). Several experiments have found that clovers tend to particularly suffer from increased O_3, more so than grasses, leading to potential changes in pasture composition (Fuhrer, 2009; Nussbaum et al., 1995; ICP Vegetation, 2011). Ozone exposure can cause visible damage to forage species, as well as increased sensitivity to pests and pathogens and a reduction in forage quality and quantity (Ashmore, 2003; Fuhrer, 2009; ICP Vegetation, 2011). The relationship between O_3 and increased CO_2

is complicated; O3 can reduce the positive effect of heightened CO_2 on plant yield (Fiscus et al., 2002), while at the same time, increased CO_2 seems to prevent some of the detrimental impact of O_3 on plantlife, though this positive effect may be reduced at higher temperatures (Fuhrer, 2009; ICP Vegetation, 2011).

Southern Europe tends to have higher O_3 concentrations than in the north and consequently its plantlife is expected to suffer more damage (ICP Vegetation, 2011). Already, spring and summer O3 concentrations often exceed thresholds for vegetation phytotoxicity and considerable damage has been observed (Fumagalli et al., 2001; ICP Vegetation, 2011). Drought tends to reduce the negative impacts of O_3 on plant life, so it may be that O_3 damage in southern Europe is greater in spring than in summer, when droughts are less common (González-Fernández et al., 2010; ICP Vegetation, 2011).

3.7 Pests and diseases

Higher temperatures could increase the incidence of diseases affecting forage plants, as the multiplication rate of soil-borne pathogens increases (Jaggard et al., 2010; Olesen, 2006). Increased CO_2 levels are also expected to favour pathogens, heightening their fecundity and aggressiveness, though this could be partially counteracted by increased host resistance (Chakraborty and Datta 2003). Control of pathogens by means of crop rotation is expected to become less effective (Jaggard et al., 2010).

Higher temperatures will also mean that insects extend their ranges to higher latitudes and altitudes, and could also expand the range of plants they consume (Bale et al., 2002). The more favourable climate and absence of long cold periods will likely lead to increasing numbers of pests, especially as overwintering could become possible (Cocu et al., 2005; Olesen, 2006; Roos et al., 2011). An example is Old World bollworm (*Helicoverpa armigera*), which has already seen a huge increase in its numbers in recent years and is expanding north from southern Europe (FAO, 2008). On the other hand, Agrell et al. (2004) studied insect-damage done to plants under elevated CO_2 and found that alfalfa damaged in this environment produces increased levels of saponins and free apigenin, reducing its exposure to the insects. Agrell et al. (2004) noted that different plant species have varying responses to the combined effects of CO_2 and herbivore damage, potentially impacting the future competitive balance within plant communities.

A longer growing season, warmer temperatures and higher CO_2 concentrations could also increase the prevalence of weeds in pastures (Kendal et al., 2013; Olesen, 2006; Tiley, 2010; Kovats et al., 2014). For example, ragweed (*Ambrosia artemisiifolia L.*) pollen production is expected to see a significant increase under climate change (Rogers et al. 2006; Wayne et al., 2002). Legumes, when they are grown in pasture-crop rotations, can reduce weed populations and break the life cycles of pests and diseases (Howieson et al., 2000).

4 Effects of climate change on small ruminants

All animals have a range of ambient temperatures, the thermo-neutral zone, below or above which can cause them stress. However, effects of extreme temperatures vary widely across species and across breeds within species (Silanikove, 2000). Comparatively speaking, sheep and goats seem to be more tolerant of climatic extremes than other farm animals but there are breed differences on how well an animal is able to respond to adverse conditions (Barnes et al., 2004). Although cold and heat stress scores are valid indicators to detect thermal stress in small ruminants, there is scarce information available regarding optimal ranges of environmental parameters for sheep and goats. Toussaint (1997) suggests that adequate temperatures for dairy goats kept indoors should range from a minimum of 6 °C to a maximum of 27 °C (optimum from 10 to 18 °C), with relative humidity ranging from 60 to 80 % and wind speed of 0.5 m/s. According to Battini et al. (2016), optimal ranges of thermal heat index (THI) for European dairy goat breeds in intensive husbandry systems are between 55 and 70, which relates to temperature and humidity ranges from 13°C to 23°C and 64 to 90%, respectively. Approximately the same ranges of temperature and humidity are considered optimal for sheep. For example, Ramón et al., (2016) observed a comfort zone between 10 and 22°C for daily average temperature and 18 and 30°C for daily maximum temperature for Manchega sheep, commonly used for milk production in intensive husbandry systems. It has previously been proposed that the lower and upper limits for thermal stress for the ovine species are 5 and 25°C, respectively; however, those limits may vary for different breeds, productive orientation (meat *vs.* milk), level of production, and climate Curtis (1983). Sheep are able to maintain remarkable thermo-stability in spite of heat stress (Degen and Shkolnik, 1978; Silanikove, 1987).

Heat stress seems to be the most important factor affecting sheep and goat production systems under climate change conditions (Wall et al., 2010), resulting in productivity losses, impairment of reproductive performance, increased disease risk and in extreme cases even death (e.g. goats: Darcan et al., 2007). In general, goats tend to tolerate heat better than sheep but are less susceptible to environmental stress than other domesticated ruminant species (see review by Lu, 1989). The vulnerability of sheep and goats to heat stress and signs of thermal stress depend on a number of environmental parameters such as temperature, humidity, indoor density, etc., but also on an animal's production status (e.g. pregnancy, lactation) and nutritional status. Breed morphological features (e.g. colour: Finch et al., 1980; hair/fleece: Acharya et al., 1995; body size: Sheridan and

Bickford, 2011) and other specific breed characteristics such as genetic production potential (e.g. sheep-milk: Singh et al., 1980; Finocchiaro et al., 2005, Maia et al., 2014; Battini et al., 2016) also play an important role in an animal's ability to cope with hot environments. The physiological adaptation of specific breeds to the environment where they live is also particularly important. European breeds are usually the least heat-adaptive because they tend to have shorter bodies and legs, short, thick ears, tight skin, and dense fleeces. In general, breeds that are typical for tropical, arid and semi-arid environments will have the highest thermal comfort zone, as they are better adapted to hot and humid conditions than those that are normally bred in temperate areas. For example, Alpine goats are more vulnerable to heat stress that Nubian goats (Brown et al., 1998). Hair sheep do well in areas of high rainfall while fine-wool sheep thrive in dry, temperate climates but have definite health problems in wet, damp climates. Medium- and coarse-wool sheep adapt to a wider range of climates while fat-tail sheep are found mainly in hot desert regions where nutritional resources are extremely limited. Other factors increase livestock's vulnerability to climate change, especially in semi-arid and arid regions such as land degradation, fragmentation of grazing area, changes in land tenure, conflicts and insecure access to land and finally markets (e.g. crop residues and by-products for feed, animal products).

To date, most studies have focused on the impact on of heat stress on sheep and goat health, welfare and productivity; whereas little information on cold stress effects is found in the literature and indicators to assess to cold stress for in on-farm welfare assessment tools are scarce. In general, the ability of animals to cope with cold extremes is highly variable and depends on both the animal´s capacity to increase heat production and the aspects affecting effective ambient temperature, but, the thermoregulatory strategies in cold stress situations, are not well documented in these species (Bøe et al., 2007).

4.1 Productivity and product quality

Temperature increases may drive an increased incidence of heat stress in sheep and goats (Al-Dawood, 2017). Heat stress has numerous consequences for animals, just one of which is impaired productivity (Lu, 1989; Marai et al., 2007; Al-Dawood, 2017, and references therein).

In studies with sheep, Peana et al. (2007) report that milk production is decreased by 30% (0.39 kg/d) when maximum and mean temperatures were higher than 21 to 24°C and 15 to 21°C respectively, while Finocchiaro et al. (2005) reports that milk production decreases by 62.8g per unit of temperature-humidity index (THI) in a Sicilian dairy breed. Similarly, Sevi et al. (2001) indicated that milk production in sheep decreases by 20% (around 70g/d) when temperatures exceed 35°C in the *Comisana* breed. In contrast, Salama et al. (2014), found a weak relationship between THI and milk yield reduction in goats, suggesting a milk decrease of 1% for every THI-unit increase (in the range of THI: 64-78). This is in line with Al-Darwood (2017)'s (and references therein) report that goats tend to tolerate heat better than sheep and seems to disappear at very high THI (THI>80), with El-Tarabany et al. (2016) reporting decreases of 27.3 and 19.3% in milk yield for high heat stress compared with low and moderate THI levels respectively in *Baladi* goats. Studies with lambs also show that heat stress impairs growth rate and body weight gain (Mahjoubi et al., 2014). Hamzaoui et al., (2013) attribute the yield reduction half due to reduced dry matter intake. In their recent experiment with dairy goats, they found that animals exposed to heat stress (12-h day at 37°C and 12-h night at 30.5°C), however, they showed a 21% decrease in dry matter intake throughout the study compared to that of control animals with no effect on milk yield. Milk quality was, however, compromised.

The negative effect of heat stress on milk quality has also been reported in a number of other studies on sheep and goats, all of which highlight the reduced total protein content of milk (Sevi et al., 2001, 2002b; Hamzaoui et al., 2012; Menéndez-Buxadera et al., 2012; Hamzaoui et al., 2013; Ramón et al., 2016). Fatty acids and total fat content can also be affected, but to a lesser extent and related to stage of lactation, parity, and season (De la Fuente et al., 2009). Sevi et al. (2002ab) found that prolonged exposure to solar radiation during summer in comparison with shaded animals led to changes in the unsaturated FA profile (-4% long to short chain FA), reduced levels of unsaturated FA and an increase of saturated FA (-13% unsaturated to saturated FA). An increased demand for thermoregulation largely affected the synthesis from body fat to milk synthesis. Salama et al. (2014) also found reduced fat concentrations in the milk of dairy goats subject to heat stress and, despite no reduction being found in their 2013 study (Hamzaoui et al., 2013), Hamzaoui et al. conclude in their 2014 paper that heat stress both changes FA composition and reduces fat concentration (Hamzaoui et al., 2014). The biohydrogenation of unsaturated FA, and a consequent reduction of MUFA and PUFA in milk, can be caused by a reduction of the rate of digesta passage in the rumen due to an increase in temperature in summer (Silanikove, 1992). The reduction of particular FA types in the summer diet can produce confounding effects on the FA milk profile. For example, Nudda et al. (2005) found that the reduction of C18:3 availability in the summer diet decreased CLA content and C18:3 VA in the milk of *Sarda* Sheep.

Coagulating properties in milk can also be impaired in summer due to the use of fat and N reserves to supply energy through gluconeogenesis at the expense of the mammary gland and reducing contents of casein and fat. Furthermore, Sevi et al. (2001) found that milk coagulation properties in the summer period were worse for sheep receiving feed during the warmest part for the day and exposed to solar radiation. Albenzio et al. (2004) also found that late lactation milk yielded during the hot season was responsible for the impairment of the coagulating properties of milk. For heat stressed goats, Abdel-Gawad et al. (2012) found that milk also had unexpected behaviour during the curd firming stage of coagulation. Such changes in coagulation properties will, have a negative impact on the cheese-making process and control operations (Salama et al., 2014). Another important issue relative to characterisation of thermal effects on milk production ability is the existence of a delayed effect of temperature on milk production. Finocchiaro et al. (2005) found that weather conditions in a 3-d period before the milk recording day yielded slightly larger estimated losses than measures on the test day or in any one of the previous 4 days.

Meat quality has been reported to be affected by exposure to events triggering stresses. When animals are exposed to higher levels of stress (isolation, cohibition, heat stress) they are prone to produce meat with a higher pH, even from the first hour of exposure to stress (Apple et al., 1993, 1995; Devine et al., 1993). The exposure to stress has a cumulative negative effect on meat quality and usually meat from stressed animals appears darker, it has greater water holding capacity (therefore higher cooking loss), it is susceptible to spoilage by micro-organisms and is it characterised by abnormal odour and taste (Apple et al., 1993, 1995; Braggins and Frost, 1997; Rana et al., 2014). Such changes are prompted by physiological responses including the release of adrenaline, anaerobic respiration and – under heat stress in particular – dehydration (Rana et al., 2014, and references therein). With some of these responses also prompted by higher temperatures in general, similar changes in quality are already seen with normal seasonal transitions (Kadim et al., 2008). This will be exacerbated as temperatures rise.

Finally, exposure to solar radiation has a detrimental effect on the hygienic quality of milk (Sevi and Caroprese, 2012). In summer, Casamassima et al. (2001) found increased somatic cell count (SCC) in milk from ewes reared indoors rather than outdoors, and attributed this to the worsening of air and litter conditions and to faecal contamination (Sevi and Caroprese, 2012).

The effects of heat stress are discussed further in Section **Errore. L'origine riferimento non è stata trovata.**

4.2 Reproduction

Small ruminants can adapt to hot climates, however, as has been shown for productivity, the response mechanisms which are helpful for survival can also be detrimental for reproductive performance (Thwaites, 1971; Sawyer, 1979). It is well established that reproduction processes are influenced by thermal exposure (Naqvi et al., 2004). In general, heat stress induces infertility in small ruminants and impacts ovarian function and conception rate; it causes silent heatearly embryonic development (Aggarwal and Upadhyay, 2012) and increases embryonic mortality (Alexandre and Mandonnet, 2005).

In females, heat stress significantly affects estrus %, duration of the gestation, conception rate, litter size and birth weight of lambs (Maurya et al., 2004). It is also well recognised that exposure to heat stress impairs normal oestrus incidences and ovulation (Naqvi et al., 2004; Tabbaa et al., 2008) and causes changes in the duration and intensity of oestrus (Younas et al., 1993). For example, exposure of ewes to high ambient temperatures for about 2 to 6 days prior to the expected oestrus occurrence has been reported to delay oestrus occurrence in ewes (Sawyer, 1979). In some cases, heat stress has been reported to influence the superovulation response in sheep and it has been reported that ewes exposed to heat stress are prone to produce poor quality embryos (Gimenez and Rodning ,2007; Naqvi et al., 2004), an effect that has been associated with impaired productivity of the offspring in adulthood (e.g., Stott and Slee, 1985). At the maternal level, heat stress before parturition, as previously reviewed, reduces milk production during the ensuing lactation (Salama et al., 2014).

For male animals, fertility is negatively affected by exposure to heat stress, as both the quantity and quality of sperm is reduced (Sahoo et al., 2013). The effects on semen can persist up to 10 weeks following exposure (Gimenez and Rodning S, 2007). High ambient temperatures also significantly increase the scrotal skin temperature in males and impact semen quality (FAO, 2015). Heat stress has further been found to reduce the normal manifestation of different sexual behaviours, which leads to a decrease in the productive potential of animals (Naqvi et al., 2012). Increased catecholamine and glucocorticoids concentrations, which mediate the inhibitory effects of stress on reproduction have also been found (Kornmatitsuk et al., 2008).

Under heat stress, the libido and fertilisation capacity of males are also significantly impaired, as found in goat rams exposed to high temperatures (above 32.2°C) (FAO, 2015). In contrast to the general consensus, Karagiannidis et al. (2000) refer to an improvement of semen characteristics of goat bucks reared in Greece during summer and autumn. However, the vast majority of the literature points to detrimental consequences – for the majority of breeds, at least.

In goat systems, rams exposed to high temperatures (above 32.2°C) have been found to have impaired reproduction. For example, overheated rams may lack libido (FAO, 2015).

There are other factors that can alter the effect of heat stress on fertility. Nutrition, for example, which is directly affected by climatic conditions in sheep and goat grazing systems, has been identified to be one of the main factors affecting ovulation rate and sexual activity (e.g. sheep: Forcada and Abecia, 2006) and nutrition modulates reproductive endocrine functions in many species including sheep (Martin et al., 2004). Also, nutrition affects reproductive function at different levels of the hypothalamus-pituitary-gonadal axis (Chadio et al., 2007).

4.3 Animal health and welfare

4.3.1 Heat stress

In view of the existing literature, the effects of heat stress on the productivity of sheep and goats has received limited attention compared, for example, to studies in dairy and beef cattle. Nevertheless, it has long been reported that sheep and goats subjected to heat stress often show a reduction in feed intake and impaired productivity (Lu, 1989; Marai et al., 2007). Heat stress also leads to behavioural and metabolic changes such as increased water intake, changes in protein, energy, and mineral metabolism and changes in enzymatic reactions and hormonal secretions (Hamzaoui et al., 2013). Other physiological responses of sheep and goats to heat stress include increases in rectal temperature, respiratory rate, heart rate and increased water evaporation (Stockman, 2006, Marai et al., 2007, El-Tarabany et al., 2016; Hamzaoui et al., 2013). Sometimes ewes exposed to solar radiation in a hot environment may not show a reduction in feed intake compared with ewes protected from solar radiation, but they had increased rectal temperature (Sevi and Caropesse, 2012).

It should be noted that changes in feed intake due to exposure to heat stress seem to be related to the type of feeds offered to the animals, and this is attributed to the amount of heat that is released during the fermentation process (Lu, 1989). For example, in experiments with goats, it has been observed that intake reduction is more profound when animals feed on roughages rather than on concentrates (Joshi et al., 1977) and that the magnitude of intake depression is reduced with inclusion of concentrates in forage-based diets (Lu, 1989; see figure 4).

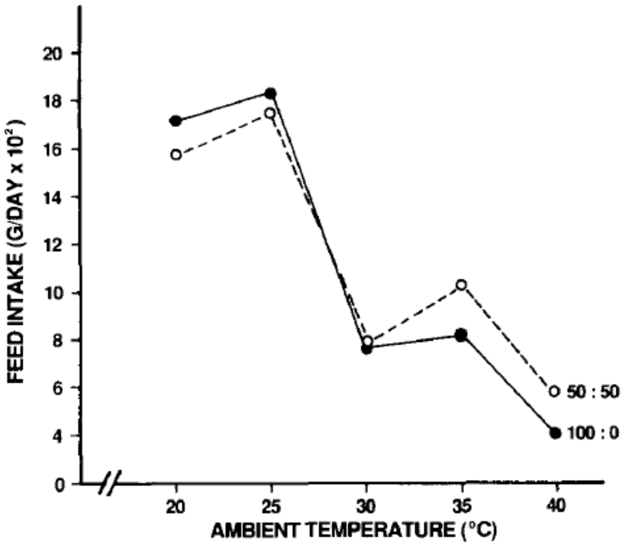

Figure 4 -Effect of ambient temperature on feed intake of Alpine goats fed a total forage diet (100:0) or a half forage-half concentrate diet (50:50) (n = 20, s.e.m. = 180 g) (adapted from Lu, 1989)

Some authors have found that the increase in water turnover (Costa et al., 1992) and the depressed passage rate of the solid phase of digesta (Bernabucci et al., 1999) are responsible for the reduction in nutrient digestibility and reduction of rumination activity during heat stress (Bernabucci et al., 2009). Reduced daily intake, associated with a decrease in volatile fatty acid concentration in the rumen and prolonged retention of feed in the gastrointestinal tract, could also increase forage digestibility (Schneider et al., 1988; Miaron and Christopherson, 1992).

4.3.2 Disease and parasites

One of the most common infectious production diseases is that of gastrointestinal nematode infections (GIN) and regardless of the parasite species, the main manifestation of GIN is the temporary depression in voluntary feed intake, i.e. anorexia, which undoubtedly contributes to reduced production efficiency of the nematode-infected sheep (Coop and Sykes, 2002; Zaralis, 2008). For example, infected lambs with *T. circumcincta* showed anorexia and had reduced growth rates in a dose-dependent manner (Symons et al., 1981; Sykes and Coop, 1976, 1977; Abbott and Holms 1983; Steel et al., 1980). Zaralis et al. (2008) also reports that susceptibility to GIN is breed related and that parasited lambs of a susceptible breed show a greater reduction in food intake. Periparturient ewes also show anorexia following infection with *T. circumcincta*, while protein supplementation can result in a reduction in faecal egg counts (Zaralis et al., 2009). It has been suggested that the detrimental consequences of GIN on animal productivity are mainly due to both anorexia and increased nutrient demand for immune response (i.e. acquisition and/or maintenance) and restoration of tissue integrity.

Although there has been some evidence of the effects of climate on developmental stages of GIN and liver fluke, the current knowledge on the respective consequences for GIN epidemiology is still very scarce (Kao et al., 2010; O'Connor et al., 2006; Kenyon et al., 2009). Nevertheless, it has been postulated that warming and environmental temperature increase is a main driver for their emergence (Fox et al., 2015). For example, the development of infective (L3) larvae within the faeces is highly influenced by environmental conditions, with temperature and relative humidity playing a key role. These factors determine both the success rate and the speed of larvae development (O'Connor et al., 2006). Lower temperatures slow the development to L3 larvae and can extend the interval to weeks rather than days. Stromberg (1997) reported from a number of studies that under optimal conditions in the laboratory at 25°C *Ostertagia ostertagi* eggs can hatch in 12 to 24 hours and develop into L3 larvae in 5-6 days, but could take up to 42 days at 5°C. This sensitivity to temperature means that development of L3 larvae from eggs deposited in early spring may take weeks, whilst taking only days for those deposited later. This tends to result in the majority of eggs reaching the infective stage at the same time, resulting in high levels of pasture infectivity from mid-summer.

Mastitis may also become more prevalent under warming. Vitali et al. (2016) demonstrate a clear correlation between incidence rate of clinical mastitis and temperature humidity index in dairy heifers and microorganisms responsible for infections of ewe udder can increase in summer because of warm environmental conditions and high relative humidity (Sevi et al., 2001). Sevi et al. (2003) found that an insufficient ventilation rate in summer determined an impairment of sheep udder health with an increase in mesophilic bacteria.

Animal welfare will be very much improved by adequate stocking density and airspace: minimal handling of animals is therefore recommended for comfort. Physical protection with artificial or natural shade is one of the most cost-effective measures to cope with the effect of heat stress on animal welfare. Garrett et al (1967) reported that shade may reduce more than 30% of all the heat radiated on an animal.

5 Potential implications of climate change on small ruminant systems in Europe

5.1 General changes and strategies in Europe for small ruminant production systems in the face of climate change

Changes in grassland productivity will affect either animal productivity or the amount of purchased feed required (Mosquera-Losada and González-Rodríguez, 1998). In a recent study, Soussana et al. (2013) indicated that in the period 1961-2005 intensification led to both (i) an increase in the proportion of arable feed over grassland herbage (decrease of 3.4% per decade) in ruminant diets and (ii) improvements in husbandry and breeding that has considerably raised feed conversion efficiency in domestic ruminants (8% per decade). According to this study, the fraction of grassland herbage will continue to decline at similar rates and ruminant feed conversion at the global scale is expected to increase at lower rates than before.

Chang et al. (2015), using the process-based vegetation model ORCHIDEE-GM, estimated changes in potential productivity and potential grass-fed ruminant livestock density across European grasslands over the period 1961–2010. Modelled results of annual grassland productivity and ruminant livestock density compared reasonably well with agricultural statistics (Eurostat and FAOstat), but tended to systematically overestimate the absolute values of productivity in most regions. When the model was run with rising CO_2 concentrations, an increase of potential annual production (over 3%) per decade was found: 97% of this increase was attributed to the rise in CO_2, -3% to climate trends and 15% to trends in nitrogen fertilisation and deposition.

Phelan et al. (2016), extrapolating a spatial relationship between bioclimatic variables and grazing season length to future climate change scenarios, predicted that for most European countries there would be a net increase in grazing season length with the increase being largest (up to 2.5 months) in the north-east of Europe. However, there were also predictions of increased variability between regions and decreases in grazing season length of up to 1.5 months in some areas such as the west of France, the south-west of Norway and the west coast of Britain. Surprisingly, they found that bioclimatic variables associated with high temperatures or dry conditions were not associated with grazing season length at current conditions. Although it is well documented that low soil moisture negatively affects grass growth, many regions in southern Europe appear to have longer observed grazing season length than we could have expected. This effect is possibly due to an adaptation measure whereby grazing managers respond to climatic stresses with lower stocking densities (particularly on sheep farms) or feed/water supplementation at pasture, rather than housing the livestock.

Bellochi et al (2014) applied the PaSim model to analyse the vulnerability of grassland production systems in Europe under different climate change scenarios. On average, a moderate increase of vulnerability of European grasslands was estimated, with significant regional differences. In particular, more vulnerable conditions was projected in the Mediterranean region. Increased vulnerability was also predicted in areas of Central-Eastern Europe and the British Isles under certain scenarios, when focusing on harvested biomass from mown grasslands. In contrast, less vulnerable conditions were predicted for grasslands in Far East Europe and high latitude regions, although certain scenarios also project an increase in vulnerability in northern Europe, due to an increased inter-annual variability of plant production (Bellochi et al., 2014).

Vulnerability to climate change and population growth will be different for the different small ruminant production systems across Europe. For example, for goat production systems, Gobger and Wall (2016) indicated that southern Mediterranean countries had the highest exposure to climate change and population growth. However, whilst Greece was found to be a very vulnerable country due to its low adaptive capacity and high risk of importing goat disease, France, Italy and Spain were found to have a large adaptive capacity to overcome the expected challenges.

In general, whereas lamb-meat production seems to be more vulnerable than small ruminant milk production in relation to the impact of climate change on disease occurrence, the opposite is found in terms of sensitivity to market fluctuations (Rancourt et al., 2006). High concentrations of susceptible hosts (i.e. lambs just after weaning which have no fully developed immunity) may potentially trigger rapid cycling-up of infection, especially if lambs co-graze with lactating ewes on pasture already infected with nematode eggs (Armour, 1986). The impact of infection on growth rates of untreated lambs is likely to be high, and financially highly significant, because of small margins and a need to finish lambs early. Milk production could be less vulnerable as it involves mainly ewes, having already, at least a proportion of them, acquired immunity to these parasites, leading to lower, more tolerable infestation intensities. However, as milk production is concentrated in warmer parts of Europe, *H. contortusis* is more likely to cause problems and immunity to this species is not as strong as to other *trichostrongylids* species.

Amongst general strategies that are applicable to all regions, increasing mixed legume-grass pastures is a good measure in order to adapt to potential shortages of global protein sources in Europe, or to face the expected decreased of protein content and digestibility of C3 grasses in non-leguminous plants under climate change conditions (e.g. Soussana et al., 1996). This also applies to an increase of grain legumes for supplementation of forages (Ianetta et al., 2016). Consistent yield benefits of mixed grass-legume swards have been reported across a wide range of climatic conditions and fertilization levels, generally outperforming the best performing monoculture (Kirwan et al., 2007; Finn et al., 2013; Multisward, 2012). Moreover, studies also indicate that multi-species mixtures can contribute to the resistance of grassland yields to drought events, which are expected to become more frequent and severe in the next decades (Hofer et al., 2016; Hoekstra et al., 2015).

In addition to presenting climate adaptive advantages over conventional pastures, these systems have lower requirements for N fertiliser through the use of biological N fixation of nodules on the roots of legumes, which would lead to energy and monetary savings, and GHG emissions reductions from both fertiliser production and use (Del Prado et al., 2011a; Zhang et al., 2013). Beyond the effects on grassland production, forages from mixed swards may also lead to a positive response at the animal level. Increased herbage voluntary intake has been observed in sheep fed indoors and in grazing cattle when more diverse forage mixtures were provided (Niderkorn et al., 2015; Peyraud et al., 2014).

The big challenge for legume-based grassland systems will be, however, persistence of legumes. Their relative abundance in mixed swards tend to decrease over time, especially under high N fertilisation levels (Lüscher et al., 2014a), but other practices, in particular sheep grazing, also appear to have a detrimental effect on legume proportion of mixed grasslands (Dumont et al., 2011). This decline has been shown to be prevented by different strategies, such as: adjusting fertilisation dosages, increasing defoliation/cutting frequency, or through an adequate pre-selection of species for enhancing more diverse mixed grass-legume swards, taking into account their competitive abilities relative to each other (Suter et al., 2012; Lüscher et al., 2014b; Husse et al., 2016; Brophy et al., 2017).

Another general measure for the conservation of soil moisture that is applicable to different climatic conditions and systems would be to implement changes in tillage practices (Del Prado et al., 2014, 2015). Reduced tillage increases resilience to climate change through improved soil fertility and increased capacity for water retention in the soil and should generate improvement in the long-term productivity potential (Olesen et al., 2011). Reduced tillage at pasture reseeding promotes C sequestration and preservation in pastures and is considered to be more effective under conditions of water deficit (Alvaro-Fuentes et al., 2011). It leads also to significant savings in CO$_2$ emissions from machinery.

For small ruminant systems largely reliant on grazing, climate change in Europe require livestock managers to deal with increased inter and intra-annual variability in forage quality dynamics. In rainy areas, ability to manipulate forage quantity and quality through grazing management, fertilisation and use of seeded forages will be very important. For southern, drier areas, adjusting the match-up between seasonal nutrient demand and supply through manipulation of the animal´s physiological state or through different mobility patterns will be more appropriate (Martin et al., 2013; Grings et al., 2016).

Goats and sheep are able to transform nutrients from poor quality feed resources into high quality animal products like milk and meat. Moreover, there is great potential for small ruminant production systems in Europe, considering future food/feed limitations, to replace some of their feeding by by-products from agro-industry. This strategy can improve resource use efficiency from these systems, enhance circular economy and decrease the effect of these systems on competition for human-edible feed resources (i. e shifting cereal-based diets to agroindustry by-products) (Mottet et al., in press; Eisler et al., 2014). Different by-products from agricultural, forestry, agro-industry and bioenergy activities can also be used for feeding ruminants as an adaptive response to forage supply seasonal constraints (e.g. Lopez and Fernandez, 2013; Ibañez et al., 2016). Rinne et al. (2012) and Vasta et al. (2008) reviewed different by-products (e.g. camelina meal, tomato pomace) that are currently underutilised but that could potentially be used as feed for low input and organic dairy production systems. Those practices are currently used as part of some livestock systems at a regional level (Correal et al., 2009). These by-products vary in their geographical availability, nutritional value, their effect on rumen methane (CH$_4$) and N excretion (i.e. effect on GHG mitigation) and have logistic-related challenges. Environmentally speaking (e.g. GHG intensity), the use of some of these by-products as animal feed may not always be the best option in comparison with their use in bioenergy or for soil improvement (Pardo et al., 2016). In this sense, removal of crop residues from cropping systems for use in bioenergy, if this means that soil C contents are being depleted (e.g. straw: Liu et al., 2014), will bring a large risk of negative impacts on adaptation measures and potentially, small or negligible positive effects on the reduction of net GHG emissions. Mitigation and adaptation conflicts may therefore arise as one chooses particular uses for one by-product or another.

Longer term adaptations can be developed through improved plant breeding. New forage resources are required that are adapted to higher temperatures, drought, and increased CO_2 (Hopkins and del Prado, 2007). This might be achieved through exploitation of traits for dehydration tolerance and summer dormancy, either in novel species or for introducing traits into existing widely used grasses and legumes (Volaire et al., 2009).

General strategies to cope with heat stress at the animal level will help decrease the effect of heat stress on small ruminant production systems. These strategies can be grouped into those related to (i) general management, (ii) genetic selection and adoption of heat resistant breeds, (iii) nutritional changes and (iv) reproductive technologies.

(i) General management: physical protection (shading), evaporative cooling (e.g. spraying: see, for example, Darcan et al., 2007) and ventilation, adequate stocking density and airspace and shearing and polling/disbudding practices.

(ii) Animals with higher resistance to heat stress: there are clear differences in resistance to heat stress between small ruminants. Those breeds that originate in tropical and arid areas, are considered the most efficient ruminants under heat stress conditions (most adaptive) and more resilient than other ruminants partly due to their low body mass and low metabolic requirements, which allows them to minimise their water and maintenance requirements. Hair sheep and fat-tailed sheep tend to tolerate heat better than wooled and thin-tailed sheep, while goats with loose skin or floppy ears tend to be most heat tolerant. Animals with horns or light coloured hair/wool are also more tolerant (Al-Dawood, 2017, and references therein). The shorter legs and bodies; short, thick ears, tight skin and dense fleeces of most European sheep, meanwhile, makes them comparatively poor at resisting heat stress (Schoenian, 2010). Although swapping to more resistant breeds is one option, this can have its own problems. Cross breeding is an alternative strategy (Al-Dawood, 2017).

Silanikove and Koluman (2014), evaluating the impact of climate change on the dairy industry in temperate zones, conclude that uttermost scenarios of climatic change will negatively affect the dairy industry and that the importance of goats to the dairy industry will increase in proportion to the severity of changes in environmental temperature. For breeds that live in temperate areas there is limited information although it is clear that breeds adapted to hot environment are less affected by heat stress.

(iii) Nutritional management: An animal with poor nutritional status will be more susceptible to environmental stresses of all kinds (Schoenian, 2010). Ensuring a nutritionally balanced diet is therefore an easy way to improve sheep and goat resistance to challenging conditions. This is particularly relevant to pasture-based systems, where the reduced grazing of animals in higher temperatures may necessitate the provision of supplementary feed. Nutritional management involves: altered feed times and intervals, the use of high energy density diets, low fibre diets , reduced rumen degradability, strategic feeding, the use of supplements (e.g. whole flaxseed), buffers (sodium bicarbonate) and feeding ingredients that help reduce drinking water consumption. (Al-Dawood, 2017, and references therein; Dumont et al., 2015). Restricting feed intake to 85% of ad libitum has also been shown to lower body temperature approximately 0.5ºC. (iv)Reproductive technologies for male and female animals will play an important role especially in the areas that are most severely impacted by heat stress.

5.2 Regional implications for small ruminant production systems in Europe

The severity of climate change impacts will vary among the different European sub-regions. Furthermore, the geographic distribution of plant species and vegetation types across Europe (Figure 4) shows the strong influence that climate has on plant growth, and the linkage with forage availability and associated livestock density and production systems (Figure 1). Accordingly, the discussion of current and projected effects of climate change on small ruminant systems and their management will focus on the five major sub-regions of the IPCC Europe region based on Metzger et al. (2005). Finally, a number of potential adaptation options are discussed.

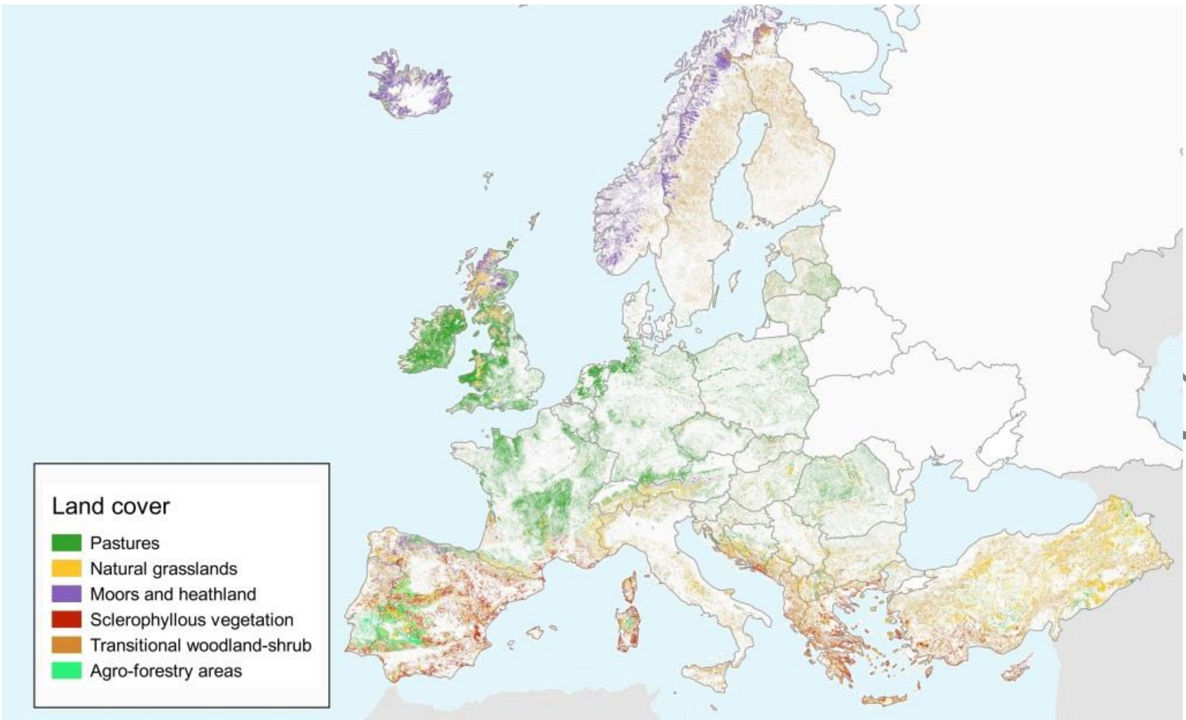

Figure 4 – Distribution of grasslands and scrublands in Europe relevant for small ruminant production.

Northern (Boreal) region

Small ruminant systems in Northern regions, although subject to similar climatic conditions, i.e. low temperature and high precipitation, are very varied. The predicted changes in climate in the Northern region are expected to lead to an increase in biomass production potential, mainly as a result of the longer growing season (earlier spring, later autumn), higher mean temperatures and decreased risk of winter-related damage from longer frost-free periods (Thorsen and Höglind, 2010). On the negative side, new stresses may emerge in relation to overwintering of perennial species (Höglind et al., 2013). Studies based on modelling approaches indicate a moderate increase in annual yields (11-14%) of timothy (*Phleum pratense L.)* and perennial ryegrass (*Lolium perenne L.*), the two most important forage grasses in Northern Europe (Höglind et al., 2013). Moreover, better overwintering conditions due to climate change may allow perennial ryegrass to grow in areas where it is not grown today, thus making possible the expansion of this grass species to new areas, provided the risk of fungal diseases does not increase (Thorsen et al., 2010). The risk of frost damage in spring was predicted to increase mainly in western parts of the study area. However, the overall trend is suggested to be reduced risk of poor grass yields (Kässi et al., 2014). If frost damage to perennial ryegrass does increase during winter, the expected increase in winter temperature due to global warming may not necessarily improve overwintering conditions, so the growing zone may not necessarily expand to the north and east of the study area. However, in the Nordic region, grass breeding should identify traits that are important for high yields under changed overwintering conditions and management practices, in order to help small ruminants adapt to climate change (Helgadóttir et al., 2016). Also, white clover (*T repens L.*) with adequate genetic variation for cold tolerance and rapid adaptive changes have been manifested (Helgadóttir et al., 2001) in northern environments.

In the Nordic area, ewes are normally housed during the winter, although with future warming it is expected that keeping adult ewes outside will become more normal. Ewes and their offspring, which are currently let out on spring pastures, will come out some weeks earlier because of warmer conditions.

Winters will continue to be long and harsh and although a lengthening of the grazing season is expected, there will still be a limited amount of fodder for about half the year. Sheep in this region are still expected to graze large areas of open heathland and grassland, including vegetation of variable productivity (Ross et al., 2016). Wet areas will have to be avoided for as long as possible. Supplementary feeding, irrespective of intensity, will therefore still normally be needed in winter. Greater possibilities for growing winter forage will allow for an increase in livestock production and/or limit the need for imported feed for small ruminant production systems. Yields of grasses and possibly feed crops are expected to increase with the warmer, moister conditions (Kochy et al., 2015 and references therein; Lehtonen et al., 2014). This is true across Europe with the exception of the Southern regions (Kochy et al., 2015 and references therein). Despite suggestion by Lehtonen et al. (2014) that variability in yield might also increase, considering the overall increase in yield alongside a reduced risk of poor yields (Kässi et al., 2014), the likelihood seems to be a net increase in feed and forage supply. When social considerations are factored in, however, prices for both producers and consumers for cereals, meat and dairy may still increase – at least under a high warming scenario (RCP 8.5) (Zimmerman et al., 2013).

Climate change is expected to have a greater positive effect on spring vegetation in mountain pasture areas compared with coastal pastures, which could result in larger lambs growing on mountain pastures under future climate warming (Nielsen et al., 2014). The great flexibility and variation in sheep production, meanwhile will help to ameliorate problems such as those due to emergence of weather-driven diseases (Dyrmundsson, 2004). Avoidance of overgrazing, which is believed to have resulted in the degradation of soils across much of the North Atlantic region (Hulme et al., 1999), will be a prerequisite for successful extensive small ruminant systems in this area. Successful management regimes will be those which can adequately support sufficient sheep densities through the sustainable production of forage plants, possibly using smaller and more traditional breeds (Ross et al., 2016).

Plants in northern regions are more sensitive to ozone injury than plants at lower latitudes, due to larger ozone influx and dim night-time light. A combination of ozone exposure and long photoperiod can lead to significant foliar injury and growth reductions in certain forb and grass species of northern Europe (Timonen et al., 2004), especially in clover species adapted to Nordic conditions (Futsaether et al., 2009, 2015; Vollsnes et al., 2009). Furthermore, the ozone influence on grassland ecosystems is not expected to be ameliorated by elevated CO_2 and may also prompt important changes in N cycling and the soil microbial community (Rämö et al., 2006). Therefore, strategies such as reducing the emission of O_3 precursors and maintaining high biodiversity are recommended in order to protect northern grassland ecosystems under future climate conditions (Manninen et al., 2009).

Atlantic region

For temperate maritime environments, e.g. the UK, climate is predicted to include warmer, wetter winters and hotter, drier summers with increased frequency of extreme weather events. Incidents of soil water-logging, floods or droughts will be increased. The combination of temperature and elevated CO_2 will enhance forage production and soil organic matter, though with considerable variation across sites, management and local climatic conditions (Riedo et al., 2000, 2001; Holden and Brereton, 2002; Graux et al., 2012; Graux et al., 2013). In addition, warming extends the growing season (Hunt et al., 1991) and shortens plant phenology (Juin et al., 2004). These impacts affect grassland and livestock management (Holden and Brereton 2002; Juin et al., 2004).

The highest positive production potential has been identified in the Atlantic region. In this area, perennial ryegrass (*Lolium perenne L.*) is the predominant grass species and annual high yields (above 10t ha^{-1}) are reached, associated with the long growing seasons due to the oceanic influence (Smit et al., 2008).

Estimations for the UK indicate that climate change will extend grazing periods and may potentially increase annual grass productivity on sheep farms (1.7-2.9 t DM ha^{-1} by 2080) (Topp et al., 2010). However, for southern latitudes and dates getting closer to the XXII century (e.g. UK: Del Prado et al., 2009) the projections suggest that grazing activity will be constrained due to overly high temperatures and excessive drought. Parsons et al. (2001) also have assessed the impact of climate change on British grazing livestock systems for the year 2050, finding that although the incidence of heat stress on ewes increased by approximately 20%, the final weight of the ewe was only reduced by about 6% due to a reduction in forage intake. This fact could easily be ameliorated by protecting the animals from direct sun on hot days. Moran et al. (2009) indicated that climate change in the UK will be within the range that sheep can cope with by behavioural means - e.g. shade use, spatial behaviour and habitat use, as long as given the opportunity to express these behaviours. Rainfall could be important if it falls at critical times of the year - especially at lambing time. Also sheep will find it hardest to cope with warm, wet weather, which is likely to lead to loss of condition and a possible increase in lamb mortality, as well as increases in foot and leg problems. Warmer winters might also lead to a reduction in housing over winter. Increased grazing season length as an adaptation choice may also result in increased exposure to helminth parasites which may be associated with reduced milk yields and a decrease in production efficiency (Kenyon et al., 2013). Neonatal lambs are likely to be the most vulnerable group since even small increases in rainfall and wind speed at lambing time can increase mortality markedly.

In some cases, extending the grazing season may be limited by the bearing capacity of the soil, driven by good soil structure degradation (e.g. poaching caused by trampling cattle and/or severe summer droughts, etc.) and therefore, it may be impractical in some cases. Therefore, avoiding compaction by traffic, tillage (Pinto et al., 2004) and grazing livestock (De Klein and Ledgard, 2005) may help to maintain grasslands in good condition and also to reduce nitrous oxide (N_2O) emissions. Extending grazing seasons by e.g. the presence of shelter/shade belts of trees would reduce the wind speed and therefore evapotranspiration (ETP). The presence of trees at low density would also increase the duration of the growing season due to their presence. Other grassland management, such as more infrequent mowing, appears more appropriate for sustaining grassland ANPP under future climate extremes (Zwicke et al., 2013).

Spring growth, provided that water resources for grass growth are available, and winter production may benefit from mild climate conditions. This can contribute to improving the farm´s degree of forage autonomy and security of livestock systems when facing more hazardous climate conditions (e.g. summer droughts) through the extension of the grazing season and the reduction of forage requirements (Graux et al., 2013). For example, forage resources usually stored for over-wintering livestock could be partially redistributed in summer to deal with increased risk of forage deficits (Graux et al., 2013).

In view of this dominant effect of a particular soil moisture level coinciding with tillage and fertilisation, it is key to find the best timing for the renewal of pasture. Velthof et al. (2010), for example, considering average Dutch climatic season conditions, suggest that this pasture renewal should take place in spring rather than fall, because Dutch autumn, compared with spring, is generally wetter and N uptake by the reseeded grass is lower. Reducing tillage has also been observed to increase the periods between which a pasture is renewed. Vellinga et al. (2004), for example, found that although tillage increased N_2O and CO_2 in the intensively managed pastures in the studied year, in the long run the renovation of the pastures was more important, preventing the deterioration of pasture quality and thus preventing significant soil and productivity losses.

Some of the traits involved in new grass breeds, e.g. improved N use efficiency in grasses (e.g. high sugar grasses: Wilkins et al., 2000) could actually be both potentially useful for climate mitigation (Del Prado et al., 2011b) and may also promote climate adaptation. They may reduce GHG emissions from urine-related N_2O emissions and improve the quality of the forage, which may be beneficial in future scenarios where climate has a detrimental effect on grass nutritional properties. New grass breeds have already been tested to improve water use efficiency and prevent flooding in areas with excessive rain. For example, in the UK, Macleod et al. (2013) tested a novel grass *Festulolium hybrid* capable of reducing runoff by 40-50% compared to a leading UK nationally recommended *L. perenne* cultivar and *F. pratensis* over a two-year field experiment. The rapid growth and turnover of roots in the hybrids resulted in greater soil water storage capacity in the plots with observed lower rainfall runoff. This may, in turn, have significant effects on N_2O emissions and soil C storage.

An increase in the establishment of rotations best suited to the area or crop rotations with legumes and annual crops (Bryan et al., 2011) may also occur as an adaptation strategy. Some crops that currently grow mostly in southern Europe will become more suitable further north or in higher altitude areas in the South. For example, forage maize may become more common across the boreal regions of Europe. Maize forage, however, tends to make the management system less flexible to inter-annual temperature/precipitation variations.

Continental region

Predicted environmental conditions in temperate areas (Atlantic and Continental regions) may allow for enhanced productivity in managed grasslands (Graux et al. 2013; Thornley and Cannell, 1997), provided an additional input of N is supplied to support the increased growth, in the form of fertiliser or through the use of N-fixing legumes (Soussana and Lüscher, 2007; Lüscher at al., 2014a).

The Continental region is also characterised by fairly high grass yields (4-8t ha-1) where the use of species such as meadow fescue (*Festuca pratensis L.*), smooth-stalked meadow grass (*Poa pratensis L.*) and timothy (*Phleum pratense L.)* plays an important role. According to modelling-based studies, in the central European area, future climate conditions may lead to a substantial yield increase of about 10-30% in the next 50 years (Weindl et al., 2015; Parton et al., 1995).

However, increased variability in climate factors and a higher frequency of extreme events (e.g. dry spells, heat waves) may mitigate the effects of gradual warming and elevated CO_2, thus constraining forage production under certain conditions (e.g. summer droughts) (Obermeier et al., 2017). To cope with such volatility, flexible management strategies will be necessary in order to optimise the high potential productivity of intensively managed temperate grasslands (Izaurralde et al., 2011).

For example, within regularly-flooded areas of central Europe, alluvial grasslands can be one of the most adequate land-use options. Flood-meadows along large lowland rivers are well adapted to flood disturbance and may tolerate long periods of submergence while exhibiting a relatively high natural productivity due to nutrient input and favourable moisture conditions (Leyer, 2002). When integrated in existing farming systems, these types of grasslands can represent an important source of high quality fodder, providing high yields without intensive management (Donath et al., 2004).

Grassland ecosystems in central and western Europe can also be very sensitive to the extreme hot and dry summer conditions more likely in future climate projections. The replacement of local phenotypes with plants of the same species more adapted to extreme climatic conditions (i.e. assisted migration) has been explored as an option for mitigating the effects of climate warming in temperate managed grasslands. However, studies indicate that this strategy may not always be effective, as regional ecotypes may outperform warm-adapted types in some cases (Beierkuhnlein, 2011; Bucharova, 2016). Enhancing the genetic diversity within populations of species is generally recommended. However, enhancing fertilisation has been also identified as an effective way of increasing drought resilience in permanent grasslands, through direct effects on productivity and through changes of functional sward composition. Greater drought resistance has been observed in grass-dominated swards than in those which are more functionally diverse (Carlsson, 2017).

With advancing climate change severity, heat stress imposed by high temperatures in temperate zones, especially during summer, may negatively impact the dairy cow industry in the continental region. In the future, this situation, together with the harsh climatic conditions predicted for the Mediterranean area, may favour the development of the goat industry in temperate zones such as central Europe (Silanikove and Koluman, 2015).

Alpine region

In Alpine grasslands, a low biomass response to elevated CO$_2$ has been observed. This lack of CO$_2$ fertilisation effect has been associated with nutrient and temperature limitations in mountainous areas, but also with carbon saturation at the ecosystem level (Körner et al., 1997). Warming trends projected in Alpine regions are expected to lengthen the growing season through an increase in spring temperatures and an earlier snow melt (Solomon et al, 2007; Wipf et al., 2010). This could lead to heightened grassland productivity (Kipling et al., 2016; Trnka et al., 2011; Kenyon et al., 2009). The projected decrease in summer rainfall may partially counteract this effect, as reduced water supply can constitute a constraint for grassland productivity in certain areas (Neuwirth et al., 2013). The extreme weather conditions, with high temperatures and low precipitation, registered in Austria in 2003 substantially affected grassland productivity in dry areas (with yield losses up to 30%), whilst having little effect in humid regions. Interestingly, no significant impact on forage quality was observed (Pöetsch et al., 2011).

This is in line with some studies in subalpine grasslands, indicating that forage quality could be enhanced as a result of warming and summer drought through an increase in water-soluble carbohydrates (Benot et al., 2013). However, the many environmental factors involved in grassland ecosystems may interact in complex ways. For example, substantial shifts in plant species and functional types were observed through transplanting experiments in the Pyrenees, associated with warming and a decrease in water availability (Sebastia et al., 2007). As a result, recalcitrant forbs were favoured against highly palatable grasses, negatively affecting forage quality.

Beyond environmental factors, mountainous habitats are also very sensitive to anthropogenic activities and therefore management decisions related to land use and livestock grazing pressure can play a crucial role in the biomass production of Alpine grasslands (Dirnböck et al., 2003; Gartzia et al., 2016; Gavazov et al., 2013).

Alpine animal breeds seem to be more sensitive to extreme heat events than those from the Mediterranean area. For example, a THI of 79 decreased milk production in Alpine but not in Nubian goats (Brown et al., 1988).

Southern (Mediterranean) region

Southern Europe is predicted to receive less rainfall and the risk of drought will increase, thus potentially reducing both forage yields and forage quality (Dono et al., 2016; Dumont et al., 2015; Sardans and Peñuelas, 2013). When climate change impacts alone are considered, a decrease in forage production has been predicted (up to 30% reduction by 2050 in some areas), due to a combination of reduced precipitation and very high temperatures (Rötter and Höhn, 2015; Dumont et al., 2015). It has been suggested that by increasing water use efficiency, heightened CO_2 levels will to some extent counteract the effects of drought on plant life (Osborne et al. 2000), though with drought conditions in southern Europe predicted to worsen it may be that this benefit is not significant (Sardans and Peñuelas, 2013; Nijs et al., 2000). The high predicted temperatures and lack of rainfall during certain periods (i.e. droughts) will lead to a lower growth potential unless land is irrigated (Gavazov et al., 2013; Del Prado et al. 2014). Dono et al. (2016) demonstrate this by applying the EPIC model to 54 000 ha in central western Sardinia, Italy. They show that by removing water stress by applying automatic irrigation, negative impacts of climate change are reversed and the probability of 'high' yields (>8.4 t DM ha^{-1}) for Italian ryegrass increase from 25% under present climate to 98.5% under predicted future climate. They infer that this benefit comes from the increase in CO_2 and temperature.

The Mediterranean zone has a traditional farm management culture that is often already well adapted to climatic variability, rather than to maximising productivity (Hopkins and Del Prado, 2007). However, in some cases, important adaptation strategies are required in order to cope with increased climatic variability and harsher conditions.

The grazing season is expected to be shortened and due to extreme events, grazing activity will also suffer from irregular patterns. An interesting management strategy to cope with different intra-year temperature and precipitation regimes, and therefore seasonal distribution of pasture, is having flexible grazing systems (Mosquera-Losada and González-Rodríguez, 1998). Also, although pasture irrigation could help alleviate the effect of droughts on grassland productivity, it is unlikely that this could be developed on a large enough scale to meet the forage demands of ruminant systems (Soussana et al., 2013).

An integrated land management approach will be necessary to maintain agriculture in the Mediterranean zone. This should incorporate soil and water protection, reduce wildfire risk in shrub and browse communities, and promote greater use of high quality silage in combination with low quality forage during dry periods (Hopkins and Del Prado, 2007).

Sheds that facilitate heat dissipation can be constructed in arid and semi-arid regions. Planting forage trees in grazing areas (introduction of silvo-pastoralism) can provide feed as well as shelter during summer. For sedentary sheep flocks, a house protected against direct wind flow with insulated roofing can also be a good strategy to maintain day temperature and to provide warmth at night. The use of bedded barns can provide shade to decrease the solar heat load on the animals. Maintaining outdoor enclosures has been shown to sustain a higher milk yield compared with indoor rearing of lactating ewes (Casamassima et al., 2001).

A reduction in annual grass productivity could lead to lower animal productivity, or else will have to be compensated with a larger share of imported feedstock, with associated monetary and environmental costs, translating into a potential loss of resilience in grassland-based livestock systems. A reduction in summer rainfall greater than 15–20% compared with the normal average value (less than expected from climate change scenarios) has been shown to be detrimental for the sustainability of semi-extensive rearing systems in a sub-Mediterranean climate (Scocco et al., 2016). Southern Europe is also projected to experience substantial crop yield losses, especially for rain-fed systems (IPCC, 2014; Olesen, 2006). As crop residues are a key feeding resource in the Mediterranean area (e.g. sheep/goat cereal mixed farming systems), particularly during dry periods, potential impacts of climate change on either the quantity or the quality of post-harvest plant residues may have important implications for the sustainability of small ruminant systems in this region (e.g. Greece: Evangelou et al., 2014; Italy: Carta et al., 1995; Spain: Rios et al., 1992). Moreover, the share of each of the feed sources from these systems (i.e. rangelands, stubble from cereal and weedy fallow fields, concentrates, cereal crops), is largely influenced by annual rainfall, as reviewed by Correal et al. (2006). During average years, the sheep-cereal system has so far been well balanced in terms of biomass productivity from each feed source. In Spain, sheep graze stubbles in summer and weedy fallows in autumn-winter. For the rest of the year, animals cover their nutritional requirements through rangeland/pasture feeding and supplemented concentrates. During dry years, cereal crops may be fully grazed and concentrate supplementation may have to be increased.

In some of these regions, acorns could supply some of these needs (Moreno and Pulido, 2009). For extensive systems, alternative forage supply may include tree leaves and shrubs, particularly in small-scale livestock farms with dry to semi-arid climates. Such species can alleviate feed shortages, or even fill feed gaps in the winter and especially in the summer, when grassland growth is limited or dormant due to unfavourable weather conditions (Papanastasis et al., 2008). Although some species have leaves with a low CP and high fibre content and contain high levels of secondary compounds such as tannins, alkaloids, saponins and oxalates, which reduce the nutritive value of poor-quality diets, some of these compounds (e.g. condensed tannins), when improved temperate forages are provided, can also have substantial benefits for ruminant productivity (i.e. reducing CH_4) and health (Waghorn and McNabb, 2003). Moreover, there are other species (e.g. *Morus alba, Fraxinus excelsior, Betula alba*) whose young leaves are rich sources of protein and fibre and which were generally used to feed animals in the past before modern techniques (e.g. fertiliser) were introduced.

Agroforestry could be a strategy for both mitigation and adaptation to climate change (e.g. IPCC, 2014b; EU forest strategy: EU, 2013) since trees and grassland soils sequester C and tree and grassland products provide a livelihood for communities, especially during drought years (Verchot et al., 2007). Besides providing feed, planting forage trees in grazing areas (introduction of silvo-pastoralism) can also provide shelter during summer, as previously mentioned. Southern Europe already hosts several agroforestry systems (e.g. Dehesa-Montado in the Iberian Peninsula) that have been shown to be good examples of the high degree of resilience, productivity and biodiversity of farmed Mediterranean landscapes in response to the fluctuating regimes and intensity caused by continuous human disturbance over many millennia (Hopkins and Del Prado, 2007). This type of system has greater resilience to climate change, due to improved soil conditions and management efficiency in water use (Kumar et al., 2011).

For the most arid regions in Europe, increases in climate variability and lengthening of the dry summer period will accelerate changes in vegetation composition, leading to shrub encroachment and will increase the proportion of bare ground, resulting in an increase in soil erosion risk. These shifts will negatively affect the carrying capacity of these systems for typical small ruminant systems in these areas and will require adjustment of livestock density to the frequency of days with ground cover. Appropriate livestock stocking rates contribute to the system's ecological stability in impeding the invasion of shrub (as is possible with undergrazing: Peco et al., 2006) and in avoiding the degradation and erosion of the soil (as with overgrazing; Schnabel, 1997).

Efforts to reintroduce desired grass species against shrub encroachment proliferation will be hindered by increased rainfall intensity (Kulmatiski and Beard, 2013), CO_2 and fire (Eldridge et al., 2012). In addition, when combined with dry conditions, high temperatures will also increase the risk of wildfires in Southern Europe. In the long term, this will threaten the fertility of soils, due to increased risk of wind and water erosion and reductions in soil nutrient availability, which ultimately can lead to a potential reduction in rangeland yields. Goat grazing is widely regarded as a wildfire prevention tool (Lovreglio et al., 2014) and could play an important role in reducing the wildfire risk in these areas.

For southern Europe, for intensive or semi-intensive systems on hot summer days, spraying has been shown to have positive effects on yearling goats for alleviating heat stress and improving animal welfare (Darcan et al., 2007). Sprayed goats consumed more concentrate feed and alfalfa hay and less water than non-sprayed groups. Moreover, sprinkling animals in the morning seemed to be more effective than in the afternoon. Evaporative cooling and a proper ventilation regime can also be effective in reducing heat stress conditions. Building orientation is also important, east-to-west is better than north-to-south. House dimensions, in particular width, are critical to air movement, minimising the inside to outside temperature gradient and maximising heat loss due to convection. Ventilation has also been shown, e.g. in ewes, to cause a decrease in psychotropic bacteria and total coliforms and SCC in milk compared with those systems without ventilation

(Albenzio et al., 2005). Providing cooling for a limited number of days early in pregnancy (when embryos are most sensitive to heat stress) can moderately improve pregnancy rates (Edwards and Hansen, 1997).

Mediterranean animal breeds have been found to be more tolerant to heat stress. However, the effect of heat stress on different breeds has been shown to be quite variable. Whereas, for example, lactating Saanen goats exposed to high THI (81 and 89) for 4 days experienced a milk loss of 3 and 13% respectively (Sano et al., 1985), Di Rosa et al. (2013) found no effect of heat stress in local breeds of goats (Camosciata) in Calabria, and Hamzaoui et al. (2012) found that early lactating Murciano-granadina dairy goats suffered greater milk yield losses (-9%) compared with late lactating animals (3%). In general 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 does not seem physiologically plausible. It must also be noted that certain tropical breeds, as well as being able to regulate body temperature in response to heat stress, are also more resistant at the cellular level, which could offer possibilities for transferring specific genes into other more sensitive breeds through conventional or transgenic breeding.

Plant breeders should focus on developing varieties that can survive long drought periods and recover rapidly following autumn rains, as well as improving adapted legume species with the following aims: reducing use of synthetic fertilisers, thus mitigating the environmental impacts of ruminant production systems; and reducing dependency on external protein-rich feeds. Forage production systems, which are commonly found in areas less suited to grain production, can contribute significantly to future food security, but only if forage crops can be successfully adapted to meet future environmental challenges. Grass-legume mixtures, however, will need to be adapted to the increased occurrence of droughts. Helgadóttir et al. (2016) suggests that to cope with these new stresses, new varieties should be created which are better adapted to new climatic conditions and/or the use of forage legumes (in pure or mixed swards) should be increased. The increased use of legumes can reduce the use of mineral fertilisers (GHG mitigation), reduce direct environmental impacts, increase the persistency of perennial grasslands to survive severe drought periods, favour C storage and biodiversity and avoid soil erosion.

In addition to new legumes, a shift to communities with more C4 grass species is a likely successional outcome in semi-natural Mediterranean grasslands, but their feeding value is lower than that of C3 species. There is a need to develop strategies for incorporation of C4 grasses, ideally with improved germplasm, into ruminant production systems (Hopkins and del Prado, 2007). Novel grasses to cope with climate change in temperate maritime environments may include hybrids involving *L. multiflorum* or *L. perenne* together with *F. arandinacea var glaucescens*, a drought and heat tolerant grass species found in Mediterranean regions (Kingston-Smith et al., 2013).

For areas which are subject to severe or extremely severe environmental stress conditions, the establishment of a community of pastures formed by species that ensure ecological stability, both in ecosystem resistance and resilience, is key as a climate change adaptation measure (Volaire et al., 2014). Biodiversity should act as a safeguard of ecosystem functioning, thus promoting a more stable ecosystem to avoid fluctuations arising from adverse climatic conditions (Volaire et al., 2014). Considering that N remains one of the main elements that determines the diversity of plants, reduced fertiliser application should be a requirement in order to increase the diversity of floral species in grasslands (Mountford et al., 1993). This reduced fertiliser input would be necessarily associated with lower emissions of N_2O per ha and potentially a greater amount of C accumulated in the soil.

Mixing Mediterranean and temperate types of tall fescue, cocksfoot and lucerne in monospecific mixtures may help to regulate forage production during the year and to reduce the disequilibrium between spring and summer production. Best adapted lucerne should focus on autumn dormancy, driven both by low temperature and short photoperiod. Mixtures of lucerne and perennial grasses for rainfed systems should be developed to meet the requirements of agriculture which is both energy- and input-limited (Helgadóttir et al., 2016). Also, the breeding of deep-rooted (e.g. tap roots) legumes and forbes and of rhizomatous grasses will have to be promoted.

Diet management will need to be modified in order to adapt to extreme heat events. For those periods, there are potential strategies to ameliorate the effect of heat on animal performance and welfare. Nutritional management involves:

- The use of high energy density diets (e.g. higher concentrates vs forage) to balance reduced feed intake and increased energy demand for thermoregulation. The addition of fat to the diet of lactating dairy ruminants is a common practice. The conversion of dietary fat to body fat is highly efficient when compared with the conversion of acetate to fatty acids (Baldwin et al., 1980). Moreover, feeding fat is associated with reduced metabolic heat production per unit of energy fed (Baldwin et al., 1980) and compared to starch and fibre, fat has a much lower heat increment in the rumen (Van Soest, 1982).

- Reduce rumen degradability: i) the use of protein with low rumen degradability to balance increased N catabolism. As has been shown for cereal-based (grain) sheep, slow fermenting grain can reduce metabolic heat and help ameliorate heat stress (Gonzalez-Rivas et al., 2016).
- Strategic feeding: changing feeding regimen, increasing number of meals and shifting meals to late afternoon and placing the feed in shaded areas.
- The use of supplements: whole flaxseed, for example, has been shown to improve CLA content in milk in ewes subject to direct exposure to solar radiation (Nudda et al., 2005; Caroprese et al., 2011) and helped immune function and physiological responses of sheep. Lupin supplementation at mating has been shown to increase net reproductive performance in lambs (Nottle et al., 1997). Other supplements that may help, such as sodium bicarbonate, may be beneficial for the production of goats under heat stress due to its buffering capacity (Lu, 1989). Some nutraceuticals (e.g. mineral and antioxidant supplementation) have been shown, with limited success (Paula-lopes et al., 2003), to improve productive and reproductive functions. Some studies (e.g. Faye et al., 2002) suggest that with supplementation, animals could withstand the effects of parasites and maintain the same level of milk production as would dewormed ones.
- Feeding ingredients that help to reduce drinking water consumption and supplementing DM and nutrients during scarcity has also been tested (Sirohi et al., 1997; Misra et al., 2006). Feeding of Kantela (*Blepharis sindica*), Azola (*Anabaena azollae*), or species of cacti seems to be a promising measure to provide feed as well as water to animals during summer feed and water scarcity.

Depending on the system and the severity of climate change in the Mediterranean area, the use of reproductive techniques will help ameliorate the effect of heat stress on fertility impairment of small ruminants. Artificial insemination with semen collected and frozen from males in cool environments can reduce the infertility risks associated with heat stress in males. For females, embryo transfer can be an effective strategy to enhance fertility, as most of the effects of heat stress that reduce fertility occur before the blastocyst stage, when embryos are typically transferred. Also, estrus induction techniques offer the chance to induce fertile estrus in non-cyclic animals, to increase fertility.

Improved estrus detection and fixed time AI can be used for overcoming the reduced expression of estrus in heat stressed animals.

6 Conclusions

Sheep and goat farming systems in Europe are linked to natural and semi-natural areas through grazing or shrubs, forest pasture and alpine grass-lands and undoubtedly contribute to biodiversity preservation, management of renewable natural sources, conservation of cultural landscapes to the socio-economic viability of many rural areas, especially in marginal areas or less favoured areas. On the other hand, it should also be noted that these systems also contribute to environmental change mainly through overgrazing that leads to soil erosion and land degradation, especially in the Mediterranean regions and through GHG emissions. Both of these aspects represent a challenge for the future of the sheep and goat sector, it should be noted however, that the important functions of the sheep and goat farming systems is neglected when comparing emissions of greenhouse gases among different livestock systems.

This review also highlights the importance that the productivity of the small ruminants is highest and occurs at a maximal efficiency if the meteorological elements are within a certain range (zone of indifference). Outside this range animals has to combat a meteorological stress which in turn impair animal productivity and health. The resulting strain varies according to species, breed, age and nutrition. Combatting meteorological stress requires extra energy, which means that less energy is available in the animal for productive processes.

Hot weather poses problems especially for the high producing genotypes with high metabolic rate as they generate more heat, which is difficult to dissipate in a hot environment. Problems of cold arise in the first place in the young animal, which is at the disadvantage of having a large surface/mass ratio, a relatively poor thermal insulation and little energy reserves. Adult animals, especially when acclimatized to cold, can tolerate low temperatures better.

From a practical point of view, knowledge derived from this Task on renewing the interrelationships between the animal and its meteorological environment can be applied in two ways: either by adapting the animal to the stressful environment by selection and breeding, or by adapting the environment to the animal by technical and managerial means. Lastly, data will be extracted from the literature reviewed in this task to develop semi-empirical meta-models in relation to the effect of weather and site conditions on pasture production and the potential adaptation measures indicated for pasture management under the iSAGE project (Task 3.2).

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