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Review Article

Grasslands in 'Old World' and 'New World' Mediterranean-climate zones: past trends, current status and future research priorities

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Abstract

Despite their ecological, economic and social importance, grasslands in areas with Mediterranean climates continue to receive limited scientific, political and media attention. The main objectives of this review are to compare and contrast dryland grasslands in the 'Old World' regions of the Mediterranean basin (southern Europe, western Asia and North Africa) with those of 'New World' regions with Mediterranean climates (Australia and Chile) and to identify common research priorities. The common characteristics and differences in climate, soils, native vegetation, importance of the livestock sector and the socio-economic background for the different Mediterranean environments are examined. Past trends and the current status of temporary and permanent Mediterranean grasslands are also described. Some common issues between these regions are as follows: (i) adaptation to climate change; (ii) increasing persistence and drought survival of both annual and perennial species; (iii) the important role of forage legumes; (iv) maintaining grassland plant diversity; and (v) improved ecosystem services, such as carbon sequestration, control of soil erosion and wildfires, and preservation of both wild and domestic biodiversity. The favourable climate in these regions, which allows year-round grazing and the growth of legumes, should be exploited to improve the sustainability of grassland-based, extensive farming systems and the quality of their animal products, while at the same time improving ecosystem services. The decreasing support for grassland research and development programmes requires increased international scientific and technical cooperation among the few institutions operating in the different Mediterranean-climate areas of the World to provide innovative and sustainable solutions to farmers.

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Introduction

Mediterranean grasslands are ecosystems which, historically, have played a vital role in the evolution of human societies (Jouven *et al.*, 2010). These ecosystems are a key component in the production of high-quality animal products (Boyazoglu and Morand-Fehr, 2001). The Mediterranean basin is a global biodiversity hotspot with an extremely high number of endemic plant species and is strongly influenced by long-term management practices (Myers *et al.*, 2000). In addition to forage quantity and quality, livestock grazing is the major driving force affecting vegetation dynamics, species distribution and landscape biodiversity (Perevolotsky, 2005; Henkin *et al.*, 2010). In this paper, we use the Peeters *et al.* (2014) definition of grasslands, as 'land devoted to the production of forage for harvest

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by grazing/browsing animals, cutting, or both'. Grassland vegetation typically includes grasses, other grass-like plants, legumes and other forbs, while woody species may also be present. Grasslands can be permanent or temporary and can consist of native vegetation, the sowing of introduced (improved) species, or a combination of both. Two management categories can be identified: (i) pastures, which are grasslands that are harvested predominantly by grazing; and (ii) meadows, which are grasslands that are harvested predominantly by mowing.

Many of the plants native to the Mediterranean basin were introduced by early European settlers to other regions with similar climates, such as southern Australia, central Chile, California and the Cape region of South Africa (Malo and Suárez, 1997; Figueroa *et al.*, 2004; Nichols *et al.*, 2012a). Such introductions were often accidental, by means of seed contaminants in fodder and wool fleeces or weed seeds in the seed lots of other agricultural plants, and became naturalized in many of the grasslands in these regions. Commercialization of well-adapted species has subsequently occurred over the past century, particularly in southern Australia, to form the basis of sown pastures. Active cultivar development programmes have operated since the 1950s with the evaluation of germplasm collected from the Mediterranean basin and more recently from breeding programmes involving crossing and selection among progeny for desirable traits (Nichols *et al.*, 2012a). This has been accompanied by the development of a specialized pasture seed industry. Many of these cultivars have subsequently been sown in the Mediterranean basin and in other Mediterranean-climate areas to improve grassland productivity.

Grassland-based farming systems are of significant importance for Mediterranean regions, satisfying the increasing demand for animal products, increasing the economic stability of smallholders and providing animal products that have high added value. Moreover, grassland-based systems are no longer seen exclusively as livestock production enterprises, but as multiple-use systems, with important consequences for the global environment (Ripoll-Bosch *et al.*, 2013). They are crucial for the protection of ecosystem goods and services, for tourism, for preventing excessive encroachment and reducing risks of wildfires, and for mitigating the impacts of climate change (Campos *et al.*, 2009; Power and Kociuba 2011). Well-managed grasslands provide important benefits such as increased water infiltration and retention and improved nutrient cycling, which are associated with soil organic matter accumulation and the diversity of species (Porqueddu *et al.*, 2003; Maes *et al.*, 2011). There is an urgent need to assess the effects of climate change on grasslands to identify appropriate options that can help farmers manage forage resources under increasing drought conditions and seasonal variability (Soussana *et al.*, 2014). The challenge is to improve grassland resilience and pasture persistence and productivity under these constraints, while at the same time reinforcing ecosystem services. Scientific advances in grassland management and new strategies in plant improvement will undoubtedly contribute to this aim (Soussana, 2014).

The main objectives of this review are to compare and contrast rainfed (non-irrigated) grassland systems in the 'Old World' Mediterranean regions of southern Europe and western Asia/North Africa (WANA) with two 'New World' regions – southern Australia and central Chile – which have similar Mediterranean climates, and to identify common research priorities.

Mediterranean environments: common features and differences

Climate

Mediterranean-climate zones are characterized by mild, wet winters and hot dry summers, and are associated with large intra- and inter-annual variability. More specifically, Buddenhagen (1990) defines a Mediterranean climate as one where mean annual precipitation ranges from 250 to 900 mm, with at least 65% occurring in the autumn-to-spring period. Some mountainous areas under humid Mediterranean climates receive more than 1200 mm of annual rainfall, with up to 80% concentrated in these months. Aschmann (1973) also claims at least 1 month should have a mean temperature below 15°C but the number of hours per year below 0°C should not exceed 3% of the annual total.

There are five regions of the world which are considered to have true Mediterranean climates: the Mediterranean basin itself (consisting of southern Europe, north Africa and west Asia), parts of southern Australia, the southern tip of South Africa, California and central Chile (Di Castri *et al.*, 1981; Dallman, 1998). Mediterranean climates occur between the latitudes 28° and 45° and are essentially transition zones between temperate climates and dry tropical climates (Dallman, 1998). They are the result of marine weather patterns which occur on the western side of continents, where cold ocean currents pass over the land. Mediterranean climate occurs on ~2% of the World's total land area (Thrower and Bradbury, 1973). The Mediterranean basin, covering ~1067 million ha, comprises ~60% of this area. These lands include the countries surrounding the Mediterranean Sea, extending east to Iraq and Iran. Approximately half of the Mediterranean area is located on the

European side of the Mediterranean basin, with over 50% dominated by grasslands (Eurostat, 2013). Of the other regions that have a Mediterranean climate, southern Australia occupies 22%, California 10%, central Chile 5% and South Africa 3% of the total area (Di Castri *et al.*, 1981). Other relatively small areas have quasi-Mediterranean-type climates with a higher proportion of summer rainfall, including parts of south-eastern Australia, New Zealand and Argentina, where plants adapted to true Mediterranean climates also grow successfully.

Soils

Soils in the Mediterranean basin

A wide variety of soils occur in the Mediterranean basin, broadly characterized by large areas of limestone of marine origin, and to a lesser extent, acidic volcanic rocks. As lime content and alkalinity have a major influence on plant growth, it is not surprising that different vegetation types occur on calcareous compared with non-calcareous substrates. Autochthone soils are more common than alluvial soils, and shallow soils with low organic matter and low nitrogen (N) and phosphorus (P) contents dominate (Day, 1983). Saline soils are quite frequent in semi-arid regions (Talamucci and Chaulet, 1989). Many soil types, especially in the northern part of the basin, are ferruginous brown soils known as '*terra rossa*' (e.g. the Castilla region in Spain), but dolomite, clayey marls, rendzines, loess, regosols, lithosols and gypsum outcrops also occur to varying degrees in many regions. In some parts of the basin, especially along the Adriatic coast and Anatolia, large karstic outcrops occur (Blondel and Aronson, 1999). According to the soil taxonomy classifications of Verheye and de la Rosa (2006), the most commonly encountered soils are as follows: (i) Xeralfs (Alfisols), which are well developed, with a clay illuviation horizon and high base saturation; (ii) Xerolls (Mollisols), typical of Mediterranean regions especially in Turkey and North Africa and characterized by xeric moisture regime with high base saturation; and (iii) Xererts (Vertisols) characterized by xeric-wet moisture regime in winter and dry in summer, of which Calcixererts which contain a (petro) calcic horizon within the surface 100 cm are the most abundant. Other common soils are Haploxerepts (shallow, often gravelly and erosion-prone), Xeropsamments (coarse textured and infertile, developed from sandy parent materials or wind-blown sands), Xerorthents (shallow, with low-humus content in the surface horizon directly overlying weathering rock in actively eroding landscapes), Natrixeralfs, a sodic soil with a natric horizon, and other saline soils.

A severe limitation to improving grassland productivity in parts of the Mediterranean basin is presented by the physical environment, characterized by young mountains, active volcanoes and a high frequency of earthquakes. This is an important surface (about 35% of the total basin lands) and constitutes a highly heterogeneous environment with small valleys, uplands, mountains and basins with steep slopes and few plains (Lapeyronie, 1982). The predominance of slopes creates difficulties for mechanization and has an increased risk of soil erosion, requiring the need for regional planning with expensive works. In most cases, coastal plains in the region are not utilized for forage production, because they have been degraded or are devoted to intensive irrigated horticulture and urbanization.

Soils of southern Australia

Although the soils of southern Australia are geologically much older than the Mediterranean basin, they are agriculturally much younger, with <200 years of farming, compared to around 10 000 years in much of the Mediterranean region. The soils of southern Australia are highly weathered and inherently infertile. Most are low in N (McDonald, 1989; Howieson *et al.*, 2008; Angus and Peoples, 2012) and P (Simpson *et al.*, 2011; Weaver and Wong, 2011) and need additional fertilizers for successful crop growth (Osborne *et al.*, 1977). In Western Australia (WA), agricultural soils are mainly sands or sandy loams, characterized by low pH and low organic matter, low total N and P, and deficiencies in trace elements such as Zn, Cu and Mo (Quinlivan *et al.*, 1973; Puckridge and French, 1983). They also tend to have poor water-holding capacity. In the higher-rainfall regions of eastern Australia the most dominant soils are red–brown earths. These generally have acidic to neutral surface pH and can store appreciable amounts of water (Puckridge and French, 1983). The semi-arid regions of eastern Australia, South Australia (SA) and the south-eastern part of WA are dominated by alkaline solonized brown soils (Puckridge and French, 1983). Much of the southern Australian landscape is salt affected, and WA is the most affected State, with around 1·1 Mha of agricultural land severely affected by dryland salinity, and a further 1·7–3·4 Mha at risk of salt-derived degradation (George *et al.*, 2008). This is due to rising water tables, caused by replacement of the native perennial vegetation by shallow-rooted annual crops and pastures.

Soils of Chile

The Mediterranean-climatic region of Chile includes the Andean foothills, the central valley, the eastern part of the coastal mountain range (the interior dryland) and the western portion of the coastal mountain range. Soils are closely associated with these physiographic areas. In the Andean foothills, soils are predominately deep Andisol loams of volcanic ash origin, with high levels of soil organic matter (SOM; 10–20%) and high water-holding capacity. These soils are slightly acidic and contain high amounts of exchangeable Al and Mn, but have low P availability, due to high P adsorption capacity (Borie and Rubio, 2003). The central valley soils are derived from moderate-to-deep fluvial–glacial deposits that are medium to fine-textured and high in organic matter (Stolpe, 2006). This area is mostly irrigated and used for fruit and seed production, with very few grasslands. In the interior dryland, soils are granitic Entisols with a sandy clay loam texture, low organic matter (1–4%) and low soil fertility. The effective depth of these soils varies with the degree of erosion, which ranges from light to very severe. Soils in the coastal mountain range are slightly acidic and are derived from granitic or metamorphic rocks; the topography is hilly and they are mostly used for forestry (pine and eucalyptus). The western side of the coastal mountain range corresponds to marine terraces, with slightly acidic, fine-textured soils of high water-holding capacity.

Native vegetation

The original climax vegetation in the World's Mediterranean regions has remarkably similar characteristics (Cody and Mooney, 1978). This is despite their isolation and indicates a high degree of convergent evolution. In the Mediterranean basin it is called *maquis*, in South Africa it is *fynbos*, in Chile *matorral* and in California *chaparral* (Cody and Mooney, 1978). In the semi-arid regions of eastern Australia, South Australia and the south-eastern part of Western Australia the native climax vegetation is known as *mallee*, after the mallee-associated *Eucalyptus* species (Puckridge and French, 1983). In south-western Australia, these regions are known as *kwongan* (Beard, 1990). The climax vegetation in each of these environments is characterized by short, deep-rooted evergreen shrubs whose leaves are usually small with high specific leaf weights (Cody and Mooney, 1978). Summer wildfires occur regularly, and the majority of climax species have evolved mechanisms to regenerate after fire (Bell *et al.*, 1993).

The native flora in the Mediterranean basin, Chile and southern Australia is highly diverse, with each of these areas considered biodiversity hotspots. The Mediterranean basin has about 25 000 species, 50% of which are endemics (Blondel and Aronson, 1999); Chile has 2395 native and 507 exotic plant species (Arroyo *et al.*, 2000; Figueroa *et al.*, 2011), while south-western Australia alone has 5710 native species (Beard *et al.*, 2000). Elevation greatly affects the local climate, and the vegetation and ecosystems that occur within these areas can be distinguished on the basis of thermal criteria (Barbero and Quézel, 1982), in addition to soil type.

The growth of human and domestic animal populations, however, has resulted in much of the climax vegetation of Mediterranean areas giving way to grasslands, which now consist primarily of annual species (Aronson *et al.*, 1993). This is particularly the case in the Mediterranean basin itself, where human disturbance over the past 10 000 years has gradually intensified, resulting in significant degradation from overgrazing and cultivation (Thompson, 1999). In other cases, a sparse tree layer has been maintained with a pasture understorey (e.g. the Iberian dehesas and montados, and the Chilean espinal). In southern Australia, much of the native vegetation has been cleared for the planting of crops and pastures.

Annual plant species that now dominate Mediterranean grasslands have evolved a suite of survival strategies that enable them to avoid the constraints of the Mediterranean climate and human-related disturbance (Norman *et al.*, 2005). Common adaptation mechanisms of annuals to disturbance include seed dormancy and delayed germination, genotypic and phenotypic responses to interactions between temperatures and moisture, and morphological traits predisposing the fruits to dispersal by grazing animals or to soil burial (Blondel and Aronson, 1999). It is for this reason that species from the Mediterranean basin have colonized the Mediterranean areas of the New World, such as Australia (Rossiter, 1966; Nichols *et al.*, 2012a), California (Allard, 1965) and Chile (Figueroa *et al.*, 2011; Martín-Forés *et al.*, 2012; Casado *et al.*, 2015).

Plant growth and forage production potential

Mediterranean climates pose significant challenges to plant growth. Plants must cope with summer drought coupled with high solar radiation levels, cool winter temperatures during the growing season, and highly erratic and variable rainfall. Germination-inducing rainfall events followed by periods of drought, referred to as 'false breaks' (Chapman and Asseng, 2001), are common and result in widespread death of establishing seedlings. The concentration of rainfall from autumn to spring and its absence during the hot summer season, accompanied by large intra- and inter-annual variability, determine a highly seasonal growth which favours annual and drought-tolerant perennial species. The very low rainfall from mid-spring to autumn results in a 300–1000-mm water deficit (Volaire *et al.*, 2009), which negatively affects plant survival and crop production. Annual plants escape this drought by forming seeds for germination in subsequent autumn–winter periods, while perennials need to have sufficient drought tolerance to survive. Growing season lengths for annual plants range from 4 to 10 months, depending on rainfall amount and timing, and reach growth peaks in spring of up to 110 kg ha^{-1} d^{-1} of dry-matter (DM) production, while a second lower peak is sometimes achieved in autumn of around 20–40 kg ha^{-1} d^{-1} of DM yield (Snaydon, 1981). Annual forage production under rainfed conditions is limited, typically ranging from 0·5 to 7·0 t of DM ha^{-1} $year^{-1}$ (Lee, 1983), but can be more than 10·0 t ha^{-1} $year^{-1}$ in high-rainfall areas.

Shrubs and pollarded trees, and the acorns of oak trees (*Quercus* spp.) are often used as forage supplements or for browsing in some parts of the Mediterranean basin (Papanastasis *et al.*, 2009). In some cases, trees constitute the main source of fodder, as in the Iranian Galazarini (Zabiholahi and Haidari, 2013).

Importance of the livestock sector and socio-economic issues

Animal production systems in the Mediterranean regions of the World are dominated by sheep and goats, while cattle-based systems are less prevalent (Table 1). The majority of goats and a high proportion of sheep reared in the European Union are present in the Mediterranean area, as cattle are better able to exploit the more favourable temperate and higher elevation areas. As variability in abiotic and biotic factors is extremely high, many different farming systems are practised in Mediterranean grassland ecosystems, especially within the Mediterranean basin. Agro-pastoral systems are prevalent in all Mediterranean regions, while agro-silvopastoral systems, involving woodland pastures and grazed shrublands, are also widespread in many parts of southern Europe and countries of the 'WANA' region (Table 1). Integration of livestock and cereal production is important in all regions, with cereal-pasture rotations (ley farming) common in the 'New World' regions of southern Australia and Chile and cereal-fallow rotations more typical in the 'Old World' regions (Table 1). Due to physical and climatic constraints, Mediterranean grassland systems are usually extensive, with low usage of pesticides, fertilizers, concentrates and irrigation (Porqueddu, 2008). Moreover, the mild winters allow year-round grazing, which provides potential advantages to farmers in terms of animal welfare and cost savings for animal housing and forage conservation (Rochon *et al.*, 2004).

There are socio-economic differences among the different Mediterranean regions (Table 1) and these have profound effects on farming systems, grassland management and sustainability issues. Land tenure in southern Australia and Chile is generally freehold and farmers are responsible for management decisions on their properties. In the southern and south-eastern part of the Mediterranean rim, and to a lesser extent in southern Europe, collective ownership and common utilization of grasslands still perpetuate in various forms, particularly in marginal lands and forests. This form of land tenure plays a pivotal role in the management of these grasslands (Boyazoglu and Flamant, 1991). In the countries of the WANA regions, much of the land belongs to the state and grazing rights are communal. Until recently, attempts to adapt legislation for these regions have failed to produce significant changes in the existing socio-tenurial approach. The use of publicly owned lands for grazing is often associated with little monitoring and planning of stocking rates, consistent with the well-known 'tragedy of the commons' argument (Hardin, 1968). The ownership arrangements, with either state-owned or community-owned lands, often lead to ecological degradation from overgrazing (Papanastasis *et al.*, 2009). Overgrazing also has socio-economic implications, as it threatens rural livelihoods and adds to deterioration of the rural economy, and thus contributes to the continuation of migration to urban areas. In southern Europe, particularly Greece, Italy and Spain, sheep flocks often graze on freehold land but are temporarily moved to graze upland pastures, which are under collective ownership. In some cases, for example in Sardinia, land tenure is spread over many small parcels, sometimes 20–25 km from the centre of the farm; these lands often occur at different elevations and are leased for agistment (Caredda *et al.*, 1992).

Population, farm size, the degree of mechanization and farm incomes differ markedly between the different Mediterranean regions (Table 1). The WANA countries have a much higher rural population (42%) than the other regions: around double that of southern Europe and Chile and about four times that of southern Australia. Average farm size on freehold land averages around 15 ha in southern Europe and <10 ha in the WANA countries. In contrast to the 'Old World' regions, the average farm size in Chile is around 100 ha, ranging from 5 to 2000 ha, while farms in southern Australia farms are much larger, averaging around 2000 ha, with some farms being >25 000 ha (Bell and Moore, 2012). The degree of

Table 1 Statistics and main farm traits for the different areas with Mediterranean-type climates.

	'Old World' regions		'New World' regions	
	Southern Europe	**West Asia/North Africa (WANA)**	**Southern Australia**	**Chile**
Area of region	~70 mill ha[a]	~997 mill ha[d]	~55 mill ha[e]	~15 mill ha
Head of sheep (m.)	40·9[b]	204·3[b]	62·7[f]	0·8[b]
Head of goats (m.)	9·5[b]	94·5[b]	0·4[g]	0·7[b]
Head of cattle (m.)	18·9[b]	77·9[b]	12·5[h,i]	0·8[b]
Prevailing farming systems	• Agropastoral, agro-silvopastoral • Livestock–cereals	• Agropastoral, agro-silvopastoral • Livestock–cereals	• Agropastoral • Livestock–cereals, ley farming	• Agropastoral • Livestock–cereals, ley farming
Prevailing animal products	• Sheep and goats for milk/cheese and meat • Cattle for meat	• Sheep and goats for milk/cheese and meat • Cattle for meat	• Sheep for meat and wool • Cattle for meat	• Sheep for meat and wool • Cattle for meat
Average farm size (ha)	15	<10	2000[j]	100
Predominant land tenure	Freehold and state- or community-owned	Freehold and state- or community-owned	Freehold	Freehold
Rural population (%)	23·2[c]	42·0[c]	10·7	18[d]
Extent of mechanization	Medium–high	Low	High	Low–medium
Farm subsidies on production	Yes	Yes	Nil	Nil

[a]Eurostat (2013);
[b]FAO (2013);
[c]World Bank (2013) data;
[d]ICARDA (2014);
[e]From Hill and Donald (1998);
[f]From Meat and Livestock Australia(2014*a*);
[g]From Meat and Livestock Australia (2014c);
[h]From Meat and Livestock Australia (2014*b*);
[i]From Dairy Australia (2014);
[j]Bell and Moore (2012).

mechanization largely reflects farm size, with Australian farms being highly mechanized. A further difference between the regions is the presence of farm subsidies in the 'Old World' countries and their absence in Australia and Chile.

Plants in Mediterranean grasslands

Northern Mediterranean basin (southern European countries)

Grasslands in the northern Mediterranean basin have played an important role in the evolution of human societies (Jouven *et al.*, 2010). Natural and semi-natural permanent grasslands represent an important ecological component by supporting animal foraging within agro-pastoral and agro-silvopastoral systems, e.g. Iberian dehesas and montados. Natural grasslands are usually species-rich, particularly for annuals, which often dominate sites, typically resulting in low annual forage production. However, increased pasture quantity and quality can be obtained from well-managed grasslands with grazing management that leads to increased legume content (Olea and San-Miguel-Ayanz, 2006).

In the past 40 years, cultivars of annual self-reseeding legumes, particularly subterranean clover (*Trifolium subterraneum* L.) and annual medics (*Medicago* species) selected in Australia, have been increasingly utilized within Mediterranean Europe, primarily for pasture improvement (Porqueddu and Gonzalez, 2006). However, these cultivars have often been poorly adapted to the variable climatic conditions and management systems of southern Europe (Sulas, 2005; Porqueddu *et al.*, 2010; Salis *et al.*, 2012). Native genotypes of these species have been selected, but efforts to promote their seed multiplication have been unsuccessful. Annual forage legumes have been traditionally used in mixtures with winter cereals (oats, barley and triticale) and grasses, especially Italian ryegrass (*Lolium multiflorum* L.), for short-term forage crops. The main species utilized are crimson clover (*Trifolium incarnatum* L.), berseem clover (*T. alexandrinum* L.), Persian clover (*T. resupinatum* L.), common vetch (*Vicia sativa* L.) and woolly pod vetch (*Vicia villosa* ssp. *dasycarpa* (Ten). Cav.).

A few species of perennial grasses, particularly phalaris (*Phalaris aquatica* L.), cocksfoot (*Dactylis glomerata* L.) and tall fescue (*Festuca arundinacea* Schreb.), are sown in higher-rainfall areas and are generally included in seed mixtures with legumes. Historically, lucerne (alfalfa; *Medicago sativa* L.) has been the primary species of temporary grassland for neutral and alkaline soils. It is utilized in pure stands as green forage or hay, or processed into dried pellets, but it may also be grazed. Under rainfed conditions, lucerne stands typically persist for 3–4 years before a rotational crop is grown. In spite of their widespread distribution in hilly areas, the perennial legumes, red clover (*Trifolium pratense* L.) and birdsfoot trefoil (*Lotus corniculatus* L.), which are adapted to moderately acidic soils, have been little sown in recent years. The same is true for sulla (*Sulla coronoria* (L.) Medik.) and sainfoin (*Onobrychis* spp.), although there is renewed interest in these perennial legumes (Re *et al.*, 2014).

A wide range of forage species is currently used in Mediterranean Europe because of the extreme variability in environmental conditions and farming systems. Seed of most of the available perennial grassland species is selected and multiplied in various countries including Central Europe, Denmark and New Zealand, whereas annuals are selected, multiplied and imported mainly from Australia. Forage seed production also occurs in Italy and France but is mainly restricted to lucerne (Huyghe *et al.*, 2014). Seed companies based in southern Europe often commercialize imported seed at low prices, then package, label and occasionally mix the seed prior to shipment. Often these products are poorly adapted to local conditions. Moreover, the seed may also be a by-product of forage or cereal crops and based on uncertified local ecotypes. Statistics used to assess seed markets can be difficult to locate and they are often unreliable (Porqueddu *et al.*, 2000).

Southern Mediterranean Basin (WANA countries)

Permanent grasslands occupy the largest land-use type in most countries of the southern Mediterranean basin. Most of the grasslands in this region exhibit arid or semi-arid climates with low and unpredictable precipitation and wide temperature fluctuations, and they generally occur on shallow and low-fertility soils with poor plant cover. Consequently, the natural vegetation has evolved with adaptations to these seasonal changes in temperature, by reducing growth rates and photosynthetic rates, mineral absorption and tissue regeneration, and by increasing concentrations of secondary metabolites (Jochum *et al.*, 2007; Belgacem and Louhaichi, 2013).

In the past, these grasslands were used extensively to provide most of the feed resources for livestock, particularly sheep and goats. However, today their contribution has been greatly reduced and in most countries natural feed resources provide <20% of livestock needs. The natural vegetation, consisting of very sparse steppe species, has been altered by anthropogenic activities. Thus, in addition to livestock overgrazing, these huge areas have been negatively affected by the encroachment of agriculture, especially barley cultivation into the most productive grazing lands, as well as frequent and excessive uprooting of shrubs for firewood and medicinal uses (Louhaichi and Tastad, 2010). These changes have resulted in reduced feed production, increased erosion and in some situations, desertification. Louhaichi *et al.* (2009) found that the diversity and structure of dominant and palatable plant species within arid and semi-arid grasslands have shifted towards less-desirable species in response to overgrazing. Other studies have also shown a shift in species composition and plant community structure as a result of overgrazing (Noy-Meir *et al.*, 1989; Westoby *et al.*, 1989).

Forage legumes have been cultivated for livestock production in the WANA region as far back in time as the Hittite era (BC 1400–1200) of Asia Minor (Karlen, 1994; Asouti and Fairbairn, 2002). Despite the antiquity of forage cultivation within this region, the current production of high-quality forages for livestock is low and substandard, as the priority for land and water resources has been reallocated to production of cereal and food legume crops (Ates *et al.*, 2014). Currently, cultivated forages in the southern Mediterranean region comprise primarily mixtures or monocultures of annual legumes and winter cereals, which occupy about 5–10% of the area allocated to cereal production. These crops are also important, albeit to a lesser extent, for grazing. Temporary grasslands, based on annual forage legumes such as *Vicia* spp., *Lathyrus* spp. and *Pisum* spp., are grown in rotation with cereal crops under rainfed conditions, whereas lucerne and berseem clover are grown as irrigated fodder crops.

Considerable effort has been devoted over the past 40 years to integrating self-regenerating annual medics into rotations with cereal crops in the region, to emulate the ley farming systems of southern Australia. However, these efforts have achieved little success, mainly due to the technical difficulties, including dependence on herbicides for weed management, low pod-set from uncontrolled grazing, burial of seed through deep ploughing and poorly adapted cultivars (Christiansen *et al.*, 2000; Howieson *et al.*, 2000; Porqueddu and González, 2011).

The agronomic and feeding value of many other temporary grassland species have been evaluated over three decades by ICARDA as a diversification strategy for improved farming systems in the southern Mediterranean region, by reducing the use of cereal monocultures and increasing the availability of high-quality livestock feed (Christiansen *et al.*, 1996; Ryan *et al.*, 2008; Larbi *et al.*, 2011). From this research, grasspea (*Lathyrus sativus* L.), common vetch and narbon vetch (*V. narbonensis* L.) have been recognized for their high potential as cool-season annual forage legumes in areas with annual rainfall of 250–350 mm (Ryan *et al.*, 2008; Larbi *et al.*, 2011; Mikić *et al.*, 2014). Hungarian vetch (*V. pannonica* Crantz) and woolly pod vetch have high cold tolerance and are suited to harsh highland conditions typical of this region (Al Moneim and Ryan, 2004). Recent studies indicate the potential for utilizing forage legumes for direct grazing or as a cut and carry system to reduce high feed costs for sheep production within the region (Rihawi *et al.*, 2010; Larbi *et al.*, 2011; Ates *et al.*, 2015). Legumes in these systems also have potential for nitrogen fixation, part of which could be available for cereal crops and thereby increase their yields.

Alternative fodder plants, particularly shrubs and cacti, are other substantial sources of livestock feed in the region (Nefzaoui and Ben Salem, 1999; Kutlu and Ozen, 2009). The integration of tree and shrub planting within private farming operations results in multiple benefits, including the production of good-quality feed for livestock. Alley cropping, a combination of desirable shrubs and herbaceous species (legumes and/or grasses), provides an excellent diet for sheep (Ben Salem, 2010b). *Atriplex* species are the most significant halophytic fodder shrubs in the region and have considerable forage potential in the arid and semi-arid grasslands of West Asia (Le Houerou, 1995). Most *Atriplex* species have high levels of crude protein, phosphorus and calcium throughout the year, at times when grasses are low in feed value. Of these, Mediterranean saltbush (*A. halimus* L.) is a particularly valuable source of forage that produces green leaves and twigs throughout the year (Ghassali *et al.*, 2011).

Spineless cactus (*Opuntia ficus-indica* var. inermis (L.) Mill.) can also play a strategic role in agricultural and economic development, due to its opportunities for income generation, food production and ecosystem conservation. Given its high water efficiency and ability to withstand extremely dry conditions, cactus is increasingly being recognized as a sustainable alternative to traditional livestock forages in many dryland areas. It generates high quantities of green forage biomass, ranging from 30 to 100 t ha^{-1} in semi-arid areas, and provides substantial amounts of essential nutrients. This high-quality forage satisfies livestock demands, reducing the intense pressure that livestock might otherwise exert on scarce water resources and other rangeland plant species (Ben Salem, 2010a). Several studies have demonstrated that additional economic benefits may be generated from incorporating cactus into ruminant diets, as it can lead to improved nutritional value arising from an increase in the proportion of conjugated linoleic acid in the meat (Ben Salem and Abidi, 2009).

Southern Australia

There is a rich history over the past century in southern Australia of developing pasture cultivars from several species to fit a diversity of representative climates and soil types. Apart from some native grasses used in high-rainfall areas of south-eastern Australia and some halophytic shrubs (particularly *Atriplex* species) in more marginal-rainfall areas, all other grassland species in southern Australia have been imported, with the vast majority originating from the Mediterranean region. The sown pasture legumes and grasses are derived from four main sources: (i) deliberate introduction of cultivated varieties from the late 18th century by the early British settlers; (ii) naturalized populations, in which seeds were accidentally brought in from other countries, leading to colonization and the development of locally adapted ecotypes; (iii) deliberate introduction of germplasm collected from the Mediterranean region; and (iv) breeding programmes, involving crossing and selection for desirable traits (Nichols *et al.*, 2012a).

Of the native grasses, the wallaby grasses (*Rytidosperma* spp.) are the most important and are often associated with *Themeda*, *Stipa*, *Poa* and *Dichelachne* species (Reed, 2014). These perennial grasses sustained much of Australia's early wool export industry and continue to be important in high-rainfall, non-arable areas of south-eastern Australia. After the Second World War, exotic perennial grasses with higher nutritive value became more widely sown in permanent and semi-permanent grasslands in the high-rainfall quasi-Mediterranean-climate zone which supports beef and dairy production, the most notable being perennial ryegrass (*Lolium perenne* L.), phalaris, tall fescue and cocksfoot.

The majority of native legumes are unsuited to the farming systems of southern Australia and many are toxic (Cocks, 2001). Lucerne was introduced by the early British settlers and has been widely used for dryland grazing and fodder conservation in south-eastern Australia. A range of annual legumes, particularly subterranean clover and annual medics, were subsequently introduced and are now widespread across the grasslands of southern Australia (Nichols *et al.*, 2012a). Subterranean clover, first marketed in 1907, is the most widely sown pasture legume in southern Australia, having been sown on moderately acidic soils over an estimated 29·3 M ha (Hill and Donald, 1998). An additional 44 cultivars have subsequently been registered, enabling it to be grown in environments with annual average-rainfall (AAR) ranging from 250–1200 mm (Nichols *et al.*, 2013). Nine annual medic species with 40 registered cultivars have been commercialized since 1938, having been sown over an estimated 24·6 M ha (Hill and Donald, 1998). These consist of the three most widely sown species: barrel medic (*M. truncatula* Gaertn), strand medic (*M. littoralis* Rhode ex Loisel) and burr medic (*M. polymorpha* L.); and the less-important species: disc medic (*M. tornata* (L.) Mill.), snail medic (*M. scutellata* (L.) Mill), sphere medic (*M. sphaerocarpos* Bertol.), gama medic (*M. rugosa* Desr.), murex medic (*M. murex* Willd.) and button medic (*M. orbicularis* (L.) Bartal.). Several other annual legume species have also been developed since the mid-1960s, particularly over the past three decades, for soil types and farming systems not suited to annual subterranean clover and annual medics. These include biserrula (*Biserrula pelecinus* L.), yellow serradella (*Ornithopus compressus* L.), French serradella (*O. sativa* Brot.), balansa clover (*T. michelianum* Savi), arrowleaf clover (*T. vesiculosum* Savi), bladder clover (*T. spumosum* L.) and Persian clover (Loi *et al.*, 2005; Nichols *et al.*, 2007).

Chile

Around 5 million ha of natural grasslands exist in the Mediterranean-climate region of central Chile, most of which (58%) is located in the arid (150–250-mm AAR) region, followed by 23% in the subhumid (400–700-mm AAR), 11% in the humid (>700-mm AAR) and 8% in the semi-arid regions (del Pozo and Ovalle, 2012). The main grazing area is the *espinal*, an anthropic savannoid formation covering ~2 million ha, characterized by dispersed trees of *Acacia caven* Mol. (espino) within a diverse grassland matrix of annual (native and exotic) and perennial (mostly native) species (Ovalle *et al.*, 1990; Arroyo *et al.*, 2000; Sax *et al.*, 2002). In the espinal agro-ecosystem, exotic species represent 49% of the herbaceous species (Martín-Forés *et al.*, 2015). The vast majority of these exotic species were introduced during the Spanish colonization period, most likely associated with imported hay, cereal seeds and large herbivores (Malo and Suárez, 1997; Figueroa *et al.*, 2004), in a similar manner to the introduction of exotic species into Australia by British settlers. Chile shares almost three-quarters of its herbaceous exotic flora with species recorded in the Iberian Peninsula (Casado *et al.*, 2015). The floristic composition of pastures differs between hillsides and flatlands, due to differences in soil moisture regimes between these two physiographic positions. Grassland species that characterize the flatlands include *Trisetum spicatum* (L.) K. Richt., *Hordeum berteroanum* E. Desv. ex Gay, *Plantago firma* Kunze ex Walp., *Leontodon leysseri* (Wallr) Beck, *Deschampsia berteroana* Fr. Meigen and *Parentucellia latifolia* Caruel, while the hillside species are *Bromus mollis* L., *Stipa laevissima*, *Erodium botrys* Bertol., *Dichondra repens* Forst., *Plantago hispidula* Ruiz and Pav. and *Trisetobromus hirtus* (Ovalle *et al.*, 2006a).

The diversity and abundance of annual legumes are low, with burr medics, cluster clover (*Trifolium glomeratum* L.) and *T. dubium* Sibth. being the most frequent species (Ovalle *et al.*, 2006a; del Pozo *et al.*, 2006).

Based on the Australian experience, the collection, introduction and evaluation of several annual legume species have been conducted over the past two decades. Initially, naturalized plant species were collected and characterized, particularly burr medic, which is widely distributed within the Mediterranean region of Chile (Paredes *et al.*, 2002; del Pozo *et al.*, 2002a,b). From this collection two cultivars were developed (Ovalle *et al.*, 2001; del Pozo *et al.*, 2001). Other annual legume species were introduced, particularly those with small and hard seeds, including biserrula (Loi *et al.*, 2015), French and yellow serradellas and balansa, arrowleaf and Persian clovers, as well as new cultivars of subterranean clover. Despite their remarkable productivity, seed yield (Ovalle *et al.*, 2005a,b; del Pozo and Ovalle, 2009) and N-fixation levels (Ovalle *et al.*, 2006b; Espinoza *et al.*, 2011) in the interior dryland and Andean foothills, the adoption of these species remains low. Moreover, mixtures of sown annual legumes (Avendaño *et al.*, 2005) have tremendous potential as a cover crop for vineyards (Ovalle *et al.*, 2010) and other fruit crops, or in rehabilitation programmes for degraded agro-ecosystems. Among the perennial legumes, lucerne and birdsfoot trefoil are used in central Chile, but mainly under irrigated conditions. Among the grasses, *Lolium* spp., tall fescue, cocksfoot and phalaris are the main sown species. Cocksfoot and tall fescue are commonly used in the Andean foothills, while cocksfoot is also used in the interior dryland and marine terraces of the coastal mountain areas.

Current status and important issues in regional grasslands

Northern Mediterranean basin

Grassland-based ecosystems play a strategic role in southern Europe because they support many local economies in marginal lands, which are often based on dairy products from sheep and goats. These systems are threatened by several factors, including increased costs, decreased availability of mineral fertilizers and irrigation water, insufficient protein feedstuff, decreased livestock prices, loss of biodiversity from overgrazing, encroachment of woody species on abandoned grazing land, changes in the EU Common Agricultural Policy and climate change (Porqueddu, 2008). The climatic, physiographic and edaphic heterogeneity associated with a large variety of vegetation types and the effects of sociocultural traditions have resulted in a complex mosaic of feed resources and integrated land use. The resultant mosaic of habitats favours a diversity of plant and animal species in agrarian landscapes (Blondel and Aronson, 1999; Benton *et al.*, 2003).

To cover the growing demand for milk, dairy products and meat, and to increase their income, many farmers have increased livestock numbers, largely through increasing stocking density. Such intensive utilization of grasslands can be attributed to the low profitability of animal production. This encourages farmers to minimize financial and labour inputs (Bouju, 2000), but often results in an over-exploitation of grassland resources. Grazing intensification can cause negative effects on vegetation and soil. In some cases, pastoralism results in a reduction in both structure and species richness of native forests, arising from tree clearing and elimination of shrubs, and favours grasses through the effects of grazing and occasional forage seeding. The landscape is, therefore, maintained by a balance between the divergent ecological processes of grazing pressure and the regeneration of trees and shrubs. Intensification produces gradual deforestation due to the lack of tree regeneration, as documented for the Iberian dehesas and other pasturelands (Plieninger *et al.*, 2010).

Inappropriate stocking rate or grazing management, in relation to available forage resources, can cause serious grassland deterioration, particularly in upland communal lands. Specific problems of land degradation caused by livestock grazing include impoverishment of the pasture cover, accelerated soil erosion caused by physical soil degradation (low soil organic matter content, low porosity, and reduced infiltration rates) and excessive N deposition from excreta (Fernández-Rebollo *et al.*, 2008; Schnabel *et al.*, 2009; Moreira *et al.*, 2011). Inappropriate machines have often been used to clear the ground of stones, to reduce shrubby and woody vegetative cover, and remove topsoil; this has led to irreversible erosion and soil degradation (Porqueddu and Roggero, 1994). The cultivation of temporary grasslands and cereals on unstable slopes has significantly increased the risks of runoff and soil loss without providing an advantage in forage yield, when compared to high-quality fertilized pastures (Porqueddu and Roggero, 1994). In Greece, a survey of citizens' opinions identified land-use changes for urban and industrial development as important threats to grasslands (Kyriazopoulos *et al.*, 2013). Since the 1960s, urban development (especially holiday housing) has rivalled traditional land uses and could lead to further degradation of natural ecosystems.

Since the mid-20th century, rainfed agriculture has been abandoned in some areas of southern Europe, mainly due to the competition from industry and tourism. This has been particularly prevalent in parts of southern France, central Italy and other mountain regions (Bouju, 2000; Pinto-Correia, 2000; Papanastasis, 2004). Such land abandonment and cessation of cropping has had negative consequences on grasslands and led to losses of both land-use diversity (Plieninger and Wilbrand, 2001) and biodiversity (Díaz *et al.*, 2013). A major effect has been the rapid encroachment of woody plants into grasslands, and woodland pastures that were formerly frequently grazed have since become very dense and ungrazable (Papanastasis, 2004; Elena-Rosselló *et al.*, 2013). Indeed, the encroachment of woody species could pose the most serious threat to European grassland ecosystems. For instance, Chouvardas and Vrahnakis (2009) reported that grassland areas near Thessaloniki, Greece, could be reduced by 96% within 10 years as a result of woody vegetation encroachment.

Several authors, including Rey Benayas *et al.* (2007) and García-Ruiz and Lana-Renault (2011), have argued that revegetation by natural succession may provide some environmental benefits, such as improvements in water regulation and nutrient cycling. There are, however, several examples of negative impacts, such as increased wildfire frequency and intensity (Moreira *et al.*, 2011), loss of cultural and aesthetic values, and a reduction in biological, floristic and landscape diversity (Bartolome *et al.*, 2005). The re-establishment of forest vegetation following soil degradation can be difficult in some of these lands, particularly in mountain areas or on water-limited dryland soils. As a result, plant colonization often transitions into shrub communities, which are prone to wildfires. For instance, more than 35% of the burned wildland in Spain occurs in shrublands, and prescribed burning has been proposed as a means of fire prevention and to maintain pastoral land values (Weir John, 2009; Vélez, 2010). This practice cannot, however, be used repeatedly without jeopardizing soil-N fertility (Casals *et al.*, 2004). Grazing is an ecological tool for the prevention of wildfires, as it significantly reduces combustible vegetation (Lovreglio *et al.*, 2014). Projects with targeted pastoral management of fire-prone grasslands have been successfully implemented in southern France (Etienne *et al.*, 1996), Italy (Pardini, 2002; Franca *et al.*, 2012) and Spain (Rigueiro-Rodríguez *et al.*, 1999; Casals *et al.*, 2009; Ruiz-Mirazo *et al.*, 2011). However, prescribed burning is still a controversial practice in other countries, such as Greece (Xanthopoulos *et al.*, 2006).

The European Union (EU) agricultural policy in relation to the GATT agreement (General Agreement on Tariffs and Trade) and the trend towards market globalization have negatively influenced the competitiveness of European Mediterranean farming systems. The acceptance by European negotiators of free-tax imports of protein-rich feedstuffs for animal feeding has led to a 400% increase in feed imports in the 27 countries of the present EU between 1961 and 2008 (FAOSTAT, 2013). The high volume of imported soya meal has supported a rapid increase in industrial-scale pig and poultry production and blocked further development of legumes and protein crops in Europe (Peeters, 2012). In the Mediterranean European regions, the Common Agricultural Policy (CAP) has provided subsidies per hectare or per head of livestock, which has played a major role in the choice by farmers of crops, animal stocking rates and land management decisions. This has tended to promote the maximization of subsidized income per farm (e.g. by increasing the number of animals), with negative cultural, social and environmental consequences and decreased economic competitiveness. Direct payments can no longer be socially justified in the context of public expense reductions, particularly while more attention is given to the preservation of natural and semi-natural permanent grasslands.

The latest EU biodiversity targets support the maintenance of many semi-natural permanent pastures in farmlands within the Natura 2000 European network of protected areas and the maintenance, enhancement and restoration of ecosystem services (EC, 2011). Unfortunately, in the 2014–2020 CAP, the definition of permanent grasslands is far too restrictive and inadequate for semi-natural grasslands and 'High Nature Value' farmland. For instance, CAP subsidies favour open pastures (based only on herbaceous forage plants) in preference to silvopastoral systems, in which the presence of trees and shrubs frequently produces a reduction in the subsidy received by farmers. This policy could seriously compromise the long-term persistence of many European silvopastoral systems, such as the Iberian dehesas and other traditionally grazed woodland pastures and shrublands.

Southern Mediterranean Basin (WANA countries)

The southern Mediterranean basin encompasses diverse agro-ecosystems with a prevalence of vegetation adapted to arid and semi-arid conditions. Livestock are a key element of these ecosystems and play an essential role in improving the livelihoods of the resource-poor and small land-area holders. Significant increases in sheep and goat populations have occurred within the region over the past two decades, associated with a rapid expansion in the demand for animal products from increased incomes, urbanization and population growth (Ben Salem and Smith, 2008; El

Kharraz *et al.*, 2012). However, capturing opportunities that arise from an increasing demand for animal products is challenged by the undue pressure on natural resources and increasing seasonal feed deficits (Aw Hassan *et al.*, 2010; Iniguez, 2011).

Current sheep and goat farming is based on low inputs and relies extensively on grazing of degraded grasslands, cereal stubbles, weedy fallow fields and barley grain supplementation (Jones, 2000). Such production systems occur predominantly in arid areas with <300-mm rainfall and constitute the main source of income for rural populations (El Moneim and Ryan, 2004). In more favourable areas, wheat-based cropping is more prevalent and livestock contribute less to farm production. Greater food security concerns have led to an increase in annual cropping of food and cash crops in both arid and semi-arid zones. This has caused conversion of large areas of grasslands to croplands and downgraded the importance of cultivated forages as a means of efficient livestock production (Nefzaoui and Ben Salem, 1999). This, along with overgrazing and recurrent droughts, has resulted in the contribution of grasslands to livestock feed gradually decreasing, from 80% in the 1980s to <30%, with the increase in barley crops now supplying a higher proportion of grain for animals (Ryan *et al.*, 2008; Belgacem and Louhaichi, 2013). On the other hand, cultivated forage crop areas have remained relatively constant, with their contribution to animal feeding being limited to <10% of the total arable area (Ates *et al.*, 2014).

In many countries in the region, governments subsidize wheat and barley prices to promote national food security (Aw Hassan *et al.*, 2010). This has encouraged continuous cereal cultivation, which in turn has led to decreases in the production of forage legumes and a long-term decline in cereal yields due to declines in soil fertility and soil organic matter, and build-up of diseases, weeds and insect pests (El Moneim and Ryan, 2004). The widespread farming of cereals in the region presents an opportunity for dual-purpose grazing and grain production systems to decrease seasonal feed deficits in early spring. Grazing dual-purpose cereal crops at the early vegetative stages and harvesting the grain at maturity has been practised by some farmers in integrated crop–livestock production systems (Francia *et al.*, 2006; Keles *et al.*, 2013) and has been recommended as a means of reducing grazing pressure on grasslands in the Mediterranean basin (Tolu *et al.*, 2012). Rodrigo *et al.* (2012) have shown that cereals can be grazed in winter without significantly compromising grain yield at the end of the season. However, greater adoption of dual-purpose management systems largely depends upon the availability of suitable cereal cultivars and the development of simple guidelines for cereal grazing.

In contrast to the northern Mediterranean, sown pastures are a minute component of traditional crop–livestock farming systems in the southern rim of the Mediterranean basin (Howieson *et al.*, 2000; Suttie *et al.*, 2005; Porqueddu, 2008). Legume-based perennial pastures present significant potential for sustainable, low-input sheep farming systems for the region (Lodge, 1994; Howieson *et al.*, 2000). Interest in sown pastures and perennial forage legumes has been increasing rapidly in some areas of the region (e.g. in Turkey), primarily due to increasing demand for feed and government subsidies on forage crops (Yolcu and Tan, 2008).

The development of indigenous forage legume cultivars, better integration of crop and livestock production, and increased efficiency of livestock production from low nutritive-value feeds are essential to agricultural sustainability in parts of the WANA region where grazing livestock is a dominant enterprise (El Moneim and Ryan, 2004; Hegarty, 2012; Ben Salem *et al.*, 2014). Diversification of production with the use of water-use efficient forage crops and inclusion of forage legumes more extensively in cropping rotations with cereals are crucial for efficient and sustainable crop–livestock production for the region's dryland production systems. The major challenges for diversifying and improving forage production, however, are the lack of improved high-yielding cultivars and poor access to locally adapted germplasm (Pecetti *et al.*, 2011).

Southern Australia

Mixed farms dominate the low- and medium-rainfall zone (<500 mm), with cropping (particularly wheat) being the major agricultural industry, supplemented by wool and meat production (prime lamb and beef). Grasslands in these areas have traditionally been based on exotic annual legumes grown in rotation with crops (Nichols *et al.*, 2007, 2012a; Wolfe, 2009). Higher-rainfall areas tend to have a higher livestock focus, with permanent or semi-permanent pastures based on annual legumes, often with the addition of temperate perennial grasses and legumes, particularly in south-eastern Australia (Wolfe, 2009; Nichols *et al.*, 2012a). Most grassland research and development has been conducted by the State government agricultural agencies, with CSIRO and Universities supporting more basic research. The funding system for grassland research differs from the other Mediterranean regions, with co-investment from meat, wool and grains Rural Research and Development Corporations, which obtain their funds from research levies paid by farmers upon the sale of produce.

The success of subterranean clover and annual medics led to adoption in the 1930s of ‘ley farming’ (Puckridge and French, 1983), a crop rotation system, whereby the pasture phase is reliant on self-regeneration from *hard* (impermeable to water) seeds, which remain dormant during a cropping phase of 1–2 years. An alternative rotation system, commonly used in eastern Australia, is ‘phase farming’, whereby 3–6 successive crops are followed by a 3–6-year phase of legume-dominated pasture (Reeves and Ewing, 1993; Nichols *et al.*, 2007); in this system, farmers must re-sow the pasture after each cropping sequence. Rapid expansion in the area of improved pastures occurred during the 1950s to 1980s, due to a wool boom and the opening of new beef markets, encouraged by government incentives for agricultural investment, the advent of aerial seeding of areas too steep for cultivation and exploitation of investments in research (Henzel, 2007; Wolfe, 2009). This was an era of large-scale pasture improvement, the so-called ‘sub and super’ revolution, based largely on widespread sowing of subterranean clover and the application of superphosphate (Wolfe, 2009). Since then, the level of inputs and perceived value of pastures have declined, due to a range of economic, social, productivity and sustainability drivers (Nichols *et al.*, 2012a).

Since the early 1970s, farmers have faced declining terms of trade of around 2·2% per annum, due to a fall in the ratio of output prices to input costs (Kingwell and Pannell, 2005). This has led to a decline in the number of farms, with the mean size of mixed farms increasing from around 1200 ha in 1975 to around 2000 ha in 2010, with some farms having more than 25 000 ha (Bell and Moore, 2012; Table 1). Farm labour decreased over this period from a mean of 1·7 full-time equivalents (FTEs) per 1000 ha in 1975 to around 1·0 FTEs per 1000 ha (Bell and Moore, 2012), largely due to increased mechanization and difficulty in attracting labour to rural areas. As in southern Europe, Australia’s farmers tend to be considerably older than other workers. In 2011, the median age of farmers was 53 years (compared with 40 years for people in other occupations) and 23% of farmers were aged 65 years or over (ABS, 2012). This median age has increased by nine years since 1981, indicating looming structural and productivity problems in the near future, unless greater incentives are provided to attract younger farmers.

Of the rural industries, wool has been particularly hard hit since the early 1990s. Increased international demand for synthetic fibres and a reduced demand for wool has resulted in a marked decline in total Australian sheep numbers from 170 million in 1990 to just under 70 million in 2015 (MLA, 2015). Low prices for wool, relative to grain, have been a major factor in this downturn, resulting in an increase in the area sown to crops at the expense of pastures (Bell and Moore, 2012). The grain legumes, lupins (*Lupinus angustifolium* L.), field peas (*Pisum sativa* L.) and faba beans (*Vicia faba* L.), and more recently, canola (*Brassica napus* L.), have been increasingly incorporated into many cropping rotations in place of forage legumes (Nichols *et al.*, 2007; Bell and Moore, 2012). Crop-pasture rotations have changed, with a higher proportion of farms reverting to continuous cropping and fewer pastures are being managed for high legume content, with crops reliant on inorganic N. The role of pastures as break crops for cereal production is being challenged by crops such as canola (oilseed rape), which can also deliver disease- and weed-management benefits. The effect of these on-farm changes has been mirrored in research-funding priorities, with increased priority given to cropping, at the expense of pastures. A major issue confronting mixed farming systems concerns management of crop weeds, with many target weeds having developed resistance to commonly used herbicides (Owen *et al.*, 2007, 2012). This has resulted in the pasture phase becoming increasingly important for delivery of weed control for the benefit of subsequent crops.

Recent trends indicate an increasing domestic and export demand in the medium to long term for sheep meat and beef. This demand, coupled with higher prices and lower costs of production relative to wool, has seen a fundamental shift away from wool towards meat production (Rowe, 2010). This is changing the demands on the feed base. While wool production is compatible with the strong seasonal nature of annual-based pastures, meat production requires a more balanced year-round feed supply. This is placing more emphasis on supplementary feeding and perennial-based pastures to provide feed outside the winter–spring growing season and provided a stimulus for developing perennial-based pasture systems.

The concept of sustainable production has developed since the 1980s, in response to the land degradation issues of soil acidification, salinization, soil erosion and compaction. Key changes to farming systems have included adding lime to correct soil acidity, replacement of plant nutrients based on soil and tissue testing, improved soil structure resulting from reduced tillage of cropping lands (linked to increased use of herbicides), and the planting of trees and increased use of perennial pastures to reduce soil erosion and the spread of dryland salinity (Dear and Ewing, 2008). A high proportion of pasture research has sought to combine increased productivity with enhanced sustainability.

Novel low-cost pasture establishment systems are being developed to stimulate increased rates of pasture sowing. One example is 'twin sowing' and 'summer sowing', which are new techniques for sowing annual legume pastures utilizing hard seed (of appropriate species) either under-sown with a grain crop (Loi *et al.*, 2008) or in dry soil over the summer (Loi *et al.*, 2012). Such systems have been made possible with the development of new rhizobia delivery systems, in the form of clay granules, which allow survival of *Rhizobium* bacteria in dry soil. The main challenge with these methods concerns effective weed control to allow legume seedlings to establish.

Pastures are becoming increasingly important for niche situations where cropping is uneconomic, particularly due to abiotic factors. Examples include the use of yellow and French serradellas and the legume shrub, tagasaste (*Chamaecytisus proliferus* L. (fil) Link ssp. *palmensis* (Christ) Kunkel) for deep infertile, acidic sands (Nichols *et al.*, 2007); saltbush (*Atriplex* spp.) for saline soils and marginal-rainfall environments (Norman *et al.*, 2010) and messina (*Melilotus siculus* (Turra) Vitman ex B.D. Jacks) for saline, waterlogged soils (Bonython *et al.*, 2011; Nichols *et al.*, 2012b). Soil acidity is increasing in many farming areas of southern Australia (Scott *et al.*, 2000). This can be overcome by the addition of lime, but if liming becomes uneconomic it will require the development of pasture plants with more acid tolerance. Phosphorus (P) fertilizer is becoming more expensive, and the response of many farmers has been to reduce their application rates, with a resultant reduction in pasture production (Simpson *et al.*, 2011; Weaver and Wong, 2011). Research is being conducted into the potential to develop more P-efficient pasture legumes, in order that the same amount of biomass can be produced with reduced inputs of P (Pang *et al.*, 2010; Simpson *et al.*, 2013).

New feedbase opportunities with perennial pasture species are being used to increase the reliability and quality of the feed supply and provide feed outside the winter-spring growing season of annual species. Their deeper roots and better water use are also being promoted to mitigate increases in dryland salinity, by reducing rainfall seepage to the water table. Summer-active, subtropical grasses are now being sown in Mediterranean areas with the mildest winter temperatures, particularly in Western Australia (Moore *et al.*, 2014), while lucerne and temperate grasses are often sown in cooler zones of south-eastern Australia (Moore *et al.*, 2006). '*Pasture cropping*' techniques, which involve the sowing of a crop into an existing perennial pasture stand, are being developed to enable farmers to capitalize on high grain prices without needing to remove the perennial pasture base (Millar and Badgery, 2009). To provide increased green feed in the summer–autumn period, a new drought-tolerant herbaceous perennial legume, tedera (*Bituminaria bituminosa* var *albomarginata* L. (syn. *Psoralea bituminosa* C.H. Stirton), has been bred (Oldham *et al.*, 2013), while several Australian native shrubs are also being explored as new options (Monjardino *et al.*, 2010). It will be important to exploit system opportunities. These may take the form of fodder shrub reserves and grazing crops to allow pasture deferment of annual legumes in the autumn–winter period (Revell *et al.*, 2012). Short-term winter grazing of cereals and canola has already become an important feeding strategy on some farms. The unreliable starts to the growing season are having a detrimental impact on annual pasture regeneration and driving increased uptake of perennials. This trend is likely to continue.

The continuing decline in the profitability of agricultural production creates an imperative for ongoing productivity improvements, and a well-supported research and development sector remains crucial for this to occur (Kingwell and Pannell, 2005; Nichols *et al.*, 2012a, 2014). However, public agencies (state and federal) have reduced their overall investment into agricultural research and development (Hunt *et al.*, 2014) and placed a high emphasis on either research into commodity supply chains or biotechnology. Investment by private enterprise has yet to fill the gaps caused by reductions in public funding. Furthermore, the introduction of Plant Breeders Rights (PBR) has not encouraged significant investment in cultivar development, due to the relatively small market size, the continued marketing of older and less-expensive public cultivars, and an inefficient capture of royalties due to losses from illegal 'over the fence' trading of PBR-protected cultivars (Revell *et al.*, 2013). The overall effect has been reduced productivity growth and market failure in plant breeding of pasture species. The release of cultivars is slowing, reflecting the lack of material reaching the end of a protracted breeding pipeline.

Chile

Grasslands in the Mediterranean region of Chile are located primarily in marginal areas. The espinal agro-ecosystem sustains a population of around 350 000 rural inhabitants and their livestock, especially sheep and goats (Vera, 2006). This production system is similar to the Spanish dehesas and Portuguese montados. Chilean grasslands have traditionally used two models of management: (i) continuous, extensive grazing in flatlands that are occasionally inundated during winter; and (ii) rotation of grazing with cereal cropping in the higher drained hillsides (Ovalle *et al.*, 1990). In the latter case, *Acacia caven* is periodically cut down for firewood and charcoal and the land is subsequently ploughed for sowing cereal crops. After the crop has been harvested, the land is abandoned and becomes colonized by herbaceous species. Shoots of *A. caven* grow from the stumps of cut plants. In this phase, the land is used for extensive grazing with a low stocking rate of ~1 sheep ha^{-1} (del Pozo *et al.*, 2006). The grazing period prior to the subsequent cropping cycle varies from 3 to 40 years, depending on soil fertility.

Today, there are higher levels of degradation in grassland areas and the espinal than has occurred historically (Aronson *et al.*, 1998). Many farmers have abandoned their traditional farming activities, due to low profitability, and they sell or hire their farms for forest plantations. As a consequence, there has been a distinct decrease in the espinal and native forested areas, and an increase in the planted area of *Pinus radiata* D.Don and *Eucalyptus globulus* Labill. (Echeverría *et al.*, 2006). There is also an increase in the areas being replaced by intensive irrigated agriculture, particularly vineyards and olive trees, leading to a reduction in the cereal area and the number of sheep.

The challenge for research is to develop appropriate technologies to increase the economic stability of farms, through improved grassland productivity and higher production of high-quality animals for export markets and domestic consumption. The rehabilitation of the degraded espinal using annual legumes and multi-purpose trees should be a priority, to increase grassland productivity and sustainability (Ovalle *et al.*, 2008). Cooperation between farmers is also necessary to increase livestock supply and negotiate better prices and conditions within the meat industry.

Deep-rooted perennial legumes can play an important role in the dryland Mediterranean areas of Chile and new germplasm of species such as lucerne, sulla, tedera, *Adesmia* spp., *Cullen australasicum*, *Lotus tenuis* and *L. corniculatus* is being examined. The focus is to identify plants with strong persistence after 4–6 months of dry summer conditions, with both high drought tolerance and high water-use efficiency during the winter–spring growing period. Evaluation and selection of adapted rhizobial strains for inoculation is also being conducted.

Common issues and research priorities

Although the Mediterranean-climate regions have strong environmental similarities, they differ markedly in their backgrounds, farming systems and socio-economic contexts. For example, overcoming problems of soil salinity and soil acidification are major constraints to grassland development in southern Australia, but these are much less important in the Mediterranean basin and Chile. The role of silvopastoral systems is very important in many European Mediterranean countries and has some importance in the Chilean espinals, but is only minor in southern Australia. Despite this, there are several common issues and research priorities for grasslands under rainfed conditions, with the common challenge of designing sustainable grassland systems. In each region, there will be a requirement for more resilient plants to provide both within- and between-season stability of biomass production under future climate change. In this context, the traits of species to cope with increasing summer drought and the potential of perennial species to increase forage production stability against a more erratic climate will be of primary importance.

The effects of climate change

Climate change, as predicted by a range of climate models, is forecast to have a great impact on agricultural production systems in regions with Mediterranean climates. The Mediterranean basin is likely to be especially vulnerable to global change, with pronounced increases in mean annual temperatures and reductions in overall precipitation, especially over the warmer months, accompanied by increased inter-annual variability (Bates *et al.*, 2008; Giorgi and Lionello, 2008). The boundaries of the Mediterranean-climate zone in southern France are reported to have moved north and north-west at a rate of 30–40 km per decade since 1980 (Lelièvre *et al.*, 2011). In south-western Australia, rainfall has declined by 10% over the past 30 years, with this decrease most evident in the autumn–winter period, while projections to 2050 indicate a further decline in rainfall, accompanied by average annual temperature increases of 0·7–1·2°C (Watterson *et al.*, 2007). Similar changes are predicted for the Mediterranean areas of Chile (NEC, 2010).

This change in climate has important implications for Mediterranean grassland productivity, and attention is needed to identify means of adapting farming systems to it. There are only limited data on grassland productivity and profitability responses to elevated temperatures, increased CO_2 levels and changes in rainfall patterns, and more bio-physical data are required to feed into models. Predictions suggest the seasonal distribution of rainfall, particularly later onset and earlier finishes to the growing season, is likely to have a stronger impact on pasture growth than reductions in total annual rainfall (Revell *et al.*, 2012; Lozano-Parra *et al.*, 2014). The predicted warmer and drier climate will also affect the grassland-ecosystem goods and services, such CO_2 sequestration, soil nutrient cycling and biodiversity (Cheddadi *et al.*, 2001).

The predicted increase in inter-annual variability has important ecological implications. For example, Aires *et al.* (2008) reported grasslands in the Portuguese montado were a moderate net source of carbon to the atmosphere in dry years and a considerable net carbon sink in high-rainfall years.

Climate change is likely to have a major long-term impact on grassland plants, particularly those whose persistence depends on soil seed banks. An assessment of biodiversity, in response to future scenarios, is needed to identify those species that are less susceptible to the effects of climate change. The adaptive capacity of these species, however, depends on their rate of adaptation to changed climatic conditions. A recent study conducted in the southern Mediterranean region indicated that reductions in desirable grassland species are likely to occur, in favour of species with low palatability and broad ecological niches, due to reduced competition for water and nutrients (Belgacem and Louhaichi, 2013). However, a meta-analysis conducted by Dumont *et al.* (2015) did not reveal significant changes in forage quality among grasses, forbs and legumes in response to elevated CO_2, warming and drought under Mediterranean conditions. Climate change is thus not expected to affect the chemical composition of individual grassland species directly, but it could result in changes to the botanical composition of grasslands (Henkin *et al.*, 2010). However, there is a need for further experiments to focus on the combined effects of increased levels of CO_2, temperature and drought on grassland productivity. The effects of extreme events have also received little investigation, although some studies suggest that responses to extreme events might differ from those obtained under moderate warming and drought (Zwicke *et al.*, 2013; Niderkorn *et al.*, 2014).

Prediction of the long-term consequences of climatic changes on species distribution and potential extinction will require detailed studies of the relationships associating these changes with the mechanisms that regulate seed bank longevity in ecosystems where population dynamics are driven primarily by environmental factors (Ooi, 2012). There is evidence, however, showing that changes in climate have occurred historically and that Mediterranean ecosystems have shown considerable resilience to these changes (Hopkins, 2012). The history of farming in the Mediterranean basin also shows that systems have evolved in response to changing conditions, and these traditions and their diversity, coupled with technological advances, provide grounds for optimism that new farming systems can be developed in response to the conditions likely under climate change scenarios.

Summer drought survival in annual and perennial species

Drought escape is the main adaptive strategy of annual pasture and forage species, as they survive the dry summer period as seeds (Ooi, 2012; Long *et al.*, 2014). In legumes, seed dormancy is determined by hardseededness (the presence of a water-impermeable seed coat; Taylor, 2005). This enables a proportion of seeds in the seed bank to remain hard (dormant) for germination in subsequent seasons, enabling regeneration after a year in which there is little or no seed set. Hardseeded legumes, therefore, have a high proportion (often >70%) of seeds that remain hard after the summer–autumn period, whereas soft-seeded legumes have only a small proportion of residual hard seeds. Hardseededness is controlled by both genetic and environmental factors during seed development (Norman *et al.*, 2002; Clua and Gimenez, 2003; Taylor, 2005; Patanè *et al.*, 2008). The amount of hard seeds and the timing of their softening differ between and within species, and in many situations the timing of seed softening may be more important than the level of hardseededness (Porqueddu *et al.*, 1996; Loi *et al.*, 2005; Nichols *et al.*, 2007). The predicted changes in rainfall distribution, consisting of relatively lower and more variable autumn rainfall and a shorter spring, mean that annual legumes will need some or all of the following traits: (i) earlier maturity for reliable seed set in shorter growing seasons; (ii) more delayed softening of hard seeds to reduce seedling losses from more prevalent false breaks; (iii) greater hardseededness to allow for more frequent seasons of little or no seed set; and (iv) a less determinate flowering habit to take advantage of longer growing seasons when they occur (Nichols *et al.*, 2012a; Revell *et al.*, 2012). Besides meteorological factors, grassland management practices may have large effects on soil seed bank dynamics. The type of grazing regime (continuous or seasonal), grazing pressure (light or heavy) and the grazing season itself all have different effects on seed bank density and on the different functional groups of plants, with heavy grazing being unfavourable to the seed bank of annuals if prolonged during seed set (Sternberg *et al.*, 2003).

Drought tolerance has great agronomic importance for the persistence of perennial forage species. Their use can extend the feeding season beyond that of annuals through increased yield during autumn–early winter and provision of additional forage in late spring, when annuals have senesced (Volaire, 2008). However, very few perennial species are suitable for the severe summer droughts and soil moisture deficits experienced in Mediterranean climates (Annicchiarico et al., 2013). The required characteristics include dormancy or low growth during the drought period (Volaire et al., 2013), survival across drought periods (Annicchiarico et al., 2011) and high water-use efficiency during the growing season. In Mediterranean areas, a combination of strategies to overcome drought are present in some plants (Volaire and Lelievre, 1997; Poirier et al., 2012; Foster et al., 2015). Plant adaptations vary, but include the following: (i) dehydration delay (avoidance), attributable to increased root development and water uptake (Volaire and Lelievre, 2001); (ii) dehydration tolerance, through osmotic adjustment (Volaire, 2008; Foster et al., 2015); (iii) reduction in stomatal conductance; (iv) leaf senescence and abscission; and (v) paraheliotropism or the turning of leaves away from direct sunlight (Foster et al., 2015).

Another adaptive response enabling plant survival of perennials during the most threatening seasons is summer dormancy, which acts to maintain meristem viability and prevents regrowth following occasional summer rainfall (Volaire et al., 2009; Lelièvre et al., 2011). Summer-dormant grasses have consistently shown superior survival over those lacking dormancy after severe and repeated summer droughts (Norton et al., 2006, 2012). Moreover, Annicchiarico et al. (2011) highlighted the need to select different adaptation targets, plant types and genetic resources for different climatic environments within Mediterranean zones. For instance, summer-dormant genotypes of *Dactylis glomerata* subsp. *hispanica* have a particular fit to the harsh climates of northern Africa. Conversely, non-dormant or incompletely dormant Mediterranean cultivars of *D. glomerata* subsp. *glomerata* are best adapted to the milder climates of southern Europe, especially when targeted to a moderate stand life (3–4 years). Nonetheless, summer-dormant germplasm could gain adaptive potential for Mediterranean regions in the future to mitigate the predicted effects of increasing drought periods. The concurrent use of plants with different strategies to overcome drought is one of the adaptation approaches proposed by Kreyling et al. (2012) to establish permanent and multi-specific grasslands with greater ecosystem stability (Volaire et al., 2013). Additionally, arbuscular mycorrhizal fungi (AMF) symbioses could significantly improve plant resistance to drought via increased dehydration avoidance (Ruiz-Lozano et al., 1995). Kyriazopoulos et al. (2014) reported that AMF have the potential to increase DM production of *D. glomerata* under drought stress. However, limited information is available concerning the selection of effective mycorrhizae to enhance forage production in Mediterranean regions.

The key role of legumes

Legumes have an important role to play in grasslands, particularly in Mediterranean regions with favourable climates for legume growth. Legumes improve the nutritional quality of forage, reducing the need for feed concentrates. Their ability to fix atmospheric N contributes to increased soil fertility and they help maintain soil organic matter and improve soil physical conditions, thereby promoting efficient low-input and low-cost production systems and reducing the need for inorganic fertilizers (Porqueddu, 2001; Sulas, 2005). Testa and Cosentino (2009), using an isotope dilution method, found the average percentage of N derived from the atmosphere (Ndfa) was 90% in lucerne, 70% in subterranean clover and up to 92% in field beans. High values of fixed N were found in sulla and lucerne, corresponding up to 184 kg ha^{-1} $year^{-1}$ (Cosentino et al., 2003; Sulas et al., 2009). When legumes are grown in pasture-crop rotations, they can reduce weed populations and break the life cycles of pests and crop diseases (Howieson et al., 2000). In permanent grasslands, the presence of a natural seed bank of pasture legumes, along with an annual application of phosphorus fertilizer, may be sufficient to gain a high legume density and increase resilience of the system, without the need for oversowing (Bullitta et al., 1989; Henkin and Seligman, 2000). In many degraded grasslands, however, soil seed banks are low and this necessitates frequent re-sowing.

A range of annual legumes, adapted to different soil and climatic conditions, are suited to different Mediterranean grassland systems. In the main, cultivars of these species have been developed by Australian scientists, based on germplasm collected from grasslands in the Mediterranean basin. Loi et al. (2005) and Nichols et al. (2007, 2012a,b; Nichols et al., 2013) describe 36 annual legume species from among the genera *Astragalus*, *Biserrula*, *Lathyrus*, *Medicago*, *Melilotus*, *Ornithopus*, *Trifolium* and *Vicia*, which have cultivars registered in Australia. Of these, subterranean clover and the annual medics have been most widely sown, both in Australia and in the other Mediterranean-climate regions. Other species that are important for particular Mediterranean zones include Persian, balansa, berseem and arrowleaf clovers, yellow and French serradellas and biserrula. A wider range of species could become more widely sown if farmers were more aware of their potential and if better-adapted genotypes were available. Cultivars developed in the Mediterranean basin and Chile would most likely result in better adaptation to local conditions, but the lack of an annual-legume seed industry in these regions precludes their commercialization.

Among perennial legumes, lucerne is well known for its drought tolerance and is valued in many farming systems for its ability to produce fodder over the warmer months. Its deep taproot allows lucerne to access soil moisture, tolerate long dry periods and respond quickly to summer rainfall (Testa *et al.*, 2011). But to extend the use of lucerne under rainfed conditions, breeding programmes are needed to enhance its forage production, persistence and tolerance to grazing in environments that are subjected to severe drought stress, high temperatures and salinity (Annicchiarico *et al.*, 2011). In southern Australia, there is also the need to select lucerne varieties, and their rhizobia, which are adapted to moderately acidic soils (Nichols *et al.*, 2012a).

Other perennial legumes such as sulla and sainfoin are able to escape summer drought through dormancy and they regrow after the first rains in autumn. Their highly flexible exploitation (grazing and/or mowing) offers an opportunity to stabilize both grassland production (in early autumn and late spring) and forage quality (Sulas, 2005; Demdoum *et al.*, 2010; Re *et al.*, 2014). Recent Australian research has focused on deep-rooted and drought-tolerant perennial legumes, including tallish clover (*Trifolium tumens* Steven ex M. Bieb.) (Hall *et al.*, 2013), Caucasian clover (*T. ambiguum* M. Bieb.), stoloniferous cultivars of red clover and more drought-tolerant genotypes of *Lotus corniculatus* (Nichols *et al.*, 2012a). Tedera also has potential as a perennial forage legume for dry areas of the Mediterranean basin, Australia and Chile (Real and Verbyla, 2010; Porqueddu *et al.*, 2011; Real *et al.*, 2011; Martınez-Fernández *et al.*, 2012; Reaside *et al.*, 2013). It originates from dry areas of the Canary Islands and has good drought tolerance due to its deep root system and other adaptive traits (Castello *et al.*, 2015; Foster *et al.*, 2015). It grows, and remains green, all-year-round and is tolerant of heavy grazing (Sternberg *et al.*, 2006). Nonetheless, seed quality and mechanized seed harvesting techniques need further investigation before it can be fully commercialized.

Although the role of legumes in improving the nutritional quality of forage is widely recognized, their nutritive value may be also be influenced by the presence of anti-quality factors (Papanastasis and Papachristou, 2000). If present in moderate concentrations, some secondary legume metabolites, such as condensed tannins, can enhance forage nutritive value by promoting amino acid absorption in the intestine (thereby decreasing nitrogen excretion and reducing greenhouse gas emissions to the atmosphere) and they may also reduce the effect of gastrointestinal parasites (Piluzza *et al.*, 2014). Moreover, forage legumes can influence meat quality in cattle (Maughan *et al.*, 2014), increase their daily average liveweight gain, and increase the linolenic and linoleic acid proportions of meat in lambs (Fraser *et al.*, 2004).

Sown grassland mixtures

The potential agronomic, environmental and economic advantages of sowing mixtures of forage species and cultivars are widely recognized (Oram, 1993; Cocks, 2001; Malhi *et al.*, 2002; Cosentino *et al.*, 2003; Nichols *et al.*, 2007; 2102a), with the main reasons being (i) better exploitation of ecological micro-niches; (ii) stabilization of forage production within and between seasons; (iii) buffering against pest and disease outbreaks; and (iv) achieving more sustainable grassland management. Grasses and herbs can utilize the nitrogen symbiotically fixed by legumes when grown in mixtures with them, leading to increases in forage dry matter and protein yield (Testa *et al.*, 2006). A coordinated field experiment across 31 European sites, including Mediterranean locations, confirmed that a mixture of four species produced significant gains in forage DM yield compared with the highest yielding monocultures at most sites (Finn *et al.*, 2013). Porqueddu and Maltoni (2007) and Maltoni *et al.* (2007) showed that grass–legume mixtures belonging to different functional groups, life cycles and rates of establishment, such as annual ryegrass (*Lolium rigidum* Gaudin), cocksfoot, burr medic and lucerne, achieved higher DM yields, better seasonal forage distribution, better weed control and higher forage quality than pure stands of each species. Mixtures of summer-dormant and summer-active perennial species and varieties also provide an opportunity for stable pasture mixtures by exploiting available soil moisture throughout the year (Norton *et al.*, 2012). However, attempts to re-create stable species mixtures have met with mixed success (Howie, 2003; Porqueddu *et al.*, 2004; Revell *et al.*, 2012). The stability and persistence of each component and their grazing management requirements need to be considered when determining mixture composition. For example, studies by Porqueddu *et al.* (2004) showed that in grazed swards sown with mixtures of annual medics, balansa clover and subterranean clover, it was the latter species that tended to dominate from the second year onwards.

There is uncertainty regarding the desired amounts of both intra- and inter-specific genetic variation in pastures to achieve and sustain an optimal economic balance between adaptation and productivity. According to Abberton *et al.* (2008), this has a significant bearing on: (i) the genetic variation to be included in future cultivars (in the case of cross-pollinated species), with uniformity implications for statutory evaluation and cultivar registration procedures; (ii) the development of mixtures of complementary cultivars, where each cultivar is differentially adapted to environmental stress; and (iii) cultivar lifetime, before they lose fitness, which influences the frequency of re-sowing. Under the suboptimal and variable environmental conditions of most Mediterranean-climate areas, the maintenance of a high level of inter- and intra-specific diversity is essential to achieve satisfactory and persistent grasslands. When the improvement or the establishment of permanent grasslands is needed, a mixture of pasture species and cultivars adapted to the environment, rather than a single species, appears more appropriate (Dear and Roggero, 2003). Nonetheless, there is little information on production, biomass composition and effects of grazing on the persistence and environmental impact of mixed swards under Mediterranean conditions, and further experimentation is required to provide information on appropriate mixture components and their management.

However, there is still a need to consider how agriculturally improved sown areas can be integrated with natural grazing areas to extend the season of fresh forage production (forage chain) by exploiting the natural seasonal growth-distribution differences that exist among forage species and varieties. Using complementary forage species, it is possible to extend the forage production season, improve forage quality and increase resource-management flexibility (Porqueddu *et al.*, 2005; Cosentino *et al.*, 2014).

Most selection and breeding programmes have focussed on growing conditions in full sunlight, and little attention has been given to selection of forage species adapted to shaded conditions, such as can be found in the Spanish dehesas, Portuguese montados and Chilean espinal. The abundance of legume species generally decreases beneath tree canopies in dehesas (Marañón *et al.*, 2009), but it is not known whether this is due to exclusion by shade or from stronger competition by deep-rooted grasses that find enough N to grow beneath the canopy. Hence, there is a need for selection programmes to develop specific seed mixtures suitable for silvopastoral purposes, where herbaceous plants have to cope with shade and competition for resources imposed by trees.

Ecosystem goods and services

Well-managed permanent grasslands produce positive externalities such as recreational activities, public goods and generic environmental services. This is particularly important in the Mediterranean basin, because they play a major role in landscape and nature conservation, mitigation of soil erosion, water protection, cultural heritage and wildfire prevention, in addition to their roles in carbon sequestration and biodiversity enhancement. These public services do not have a market price, however; they are difficult to disaggregate, are highly interrelated in complex dynamic ways and are therefore difficult to measure. Possible synergies and trade-offs among different ecosystem services need to be identified. The strong links between grassland-based livestock production and the provision of diverse ecosystems goods and services, especially in mountain and other marginal areas, need to be considered and integrated into a standard evaluation framework for environmental impacts of agricultural production, such as Life Cycle Assessment (Ripoll-Bosch *et al.*, 2013).

Carbon sequestration

Natural grasslands account for 10–30% of the World's total soil organic carbon (Brevik, 2012), thereby playing an important role in the global carbon cycle. Soil organisms decompose dead plant matter, leading to the recycling of nutrients for plant growth and releasing C, in the form of CO_2, to the atmosphere (Doran, 2002). However, this has been little studied in Mediterranean grasslands. One field experiment conducted over 7 years showed that in pastures sown initially to Italian ryegrass, and later intercropped with subterranean clover, the soil organic matter (SOM) increased from 1·58% to 1·66% (representing an equivalent of 2·6 t year^{-1} of stored CO_2), while plots cultivated with durum wheat showed a slight decrease (Cosentino *et al.*, 2013). In plots with lucerne, a continuous increase in SOM (from 1·02% to 1·39%) was observed during four years, corresponding to an average of 7·4 t ha^{-1} of CO_2 stored. Coordinated experiments in different Mediterranean regions are required to quantify the carbon sequestration contribution of natural and semi-natural grasslands, as well as the contributions of key pasture species.

Soil erosion control

Mediterranean areas with hills and slopes are particularly susceptible to soil erosion from heavy rainfall. According to Plan Bleu (2003), the area of land subjected to soil erosion in the Mediterranean basin covers 1 309 000 km^2, equal to 15% of the land of Mediterranean countries. Similar soil erosion issues on hillsides occur in Chile and southern Australia. Steep slopes with fragile soils can suffer considerable soil erosion from intense rainfall following a long dry summer. This leads to a reduction in cultivable soil depth and reduced soil fertility from a loss of organic matter and nutrients (Van Rompaey *et al.*, 2005). In such environments, the growing cycle of winter cereals and annual forage crops results in a lack of soil cover during the summer and this leaves the soil surface prone to erosion from the first autumn and winter rains.

This was demonstrated on a 26–28% slope in Sicily by Cosentino *et al.* (2011), who recorded yearly soil loss in annual tilled crops of 11–23 t ha^{-1} year^{-1}, compared to 0·15–1·8 t ha^{-1} year^{-1} in permanent sown grasslands. In a similar experiment conducted in Sardinia, Porqueddu and Roggero (1994) showed that on a 30% slope, average annual soil losses were ten times greater from annual forage crops than permanent grassland and twenty times greater on bare soil than on permanent grassland. Furthermore, the annual forage crops did not give a greater DM yield than fertilized permanent pasture. Schnabel *et al.* (2013) showed a relationship between cover of vegetation cover in the Iberian dehesas and soil loss for different rainfall intensities. When vegetation covered more than 60% of the ground surface, even exceptionally intense storms (>40 mm h^{-1}) produced soil losses of <0·3 t ha^{-1}, whereas significant soil losses occurred from moderately intense storms when ground cover of vegetation was <20% (which commonly occurs with a moderate stocking density during a prolonged drought).

Overgrazing by livestock is considered one of most important causes of soil erosion and consequent desertification in Mediterranean regions (Papanastasis, 1998). Overgrazing decreases vegetation cover as well as above-ground and below-ground plant biomass and thus makes the soil more erosion-prone. These effects are highly dependent on soil structure, slope and rainfall duration and intensity. In arid and semi-arid areas, this problem is exacerbated by drought. Sustainable grazing management is, therefore, an essential tool to combat soil erosion, land degradation and desertification in these areas.

Biodiversity

The abandonment of husbandry, the intensification of agricultural practices and climate change in several Mediterranean areas are of concern environmentally, as they can dramatically alter soil characteristics and impact on local flora and fauna communities (Rosa Garcìa *et al.*, 2010; Osoro *et al.*, 2012). All these disturbance factors impact on biodiversity, which constitutes the most important stability factor of natural and agricultural ecosystems (Brussaard *et al.*, 2010; Fontaine, 2011). Rosa Garcìa *et al.* (2013) underlined that halting and reversing the decline of permanent grasslands is one of the biggest challenges for the maintenance of European biodiversity and wider ecosystem services (including the Mediterranean areas) and that the development of proper management strategies is fundamental.

According to Sala *et al.* (2000), Mediterranean grassland ecosystems will most likely experience a greater proportional change in biodiversity than is likely in northern temperate ecosystems, because of the substantial influence of the key drivers of biodiversity change. The consistent effects of species richness on multi-functionality, over and above those of climate and abiotic factors, highlight the importance of plant biodiversity as a driver of multi-functionality in drylands. Temporal stability of the ecosystem increases with diversity, despite a lower temporal stability of individual species.

Typical Mediterranean agroforestry systems (i.e. dehesa types) represent an archetypal example of high nature value (HNV) farmland (Oppermann *et al.*, 2012), because their use as grazing lands enhances herbaceous diversity indices. Studies of appropriate agroforestry management practices for trees and grasslands are important for conserving diversity and productivity of dehesa-type systems under the conditions of high climatic and soil variability in Mediterranean environments (López-Carrasco *et al.*, 2015; Rolo *et al.*, 2015).

Bioenergy from grassland

Biomass from permanent grasslands generally has high hemicellulose and cellulose and low lignin contents and could be successfully used as feedstock for second-generation ethanol production. Delayed harvests can result in high structural polysaccharide levels (Prochnow *et al.*, 2013), the primary substrates for ethanol production. In typical Mediterranean grassland, the hemicellulose content decreases when harvest is delayed from the beginning to the end of summer, while the cellulose content increases (Martillotti *et al.*, 1996). Although there is seldom any excess of pasture herbage availability under rainfed conditions in the Mediterranean regions of southern Europe, increasing land abandonment makes the use of grasslands for bioenergy an option. However, given the multiple functions that grasslands and grassland landscapes provide to society in this region, the use of grassland vegetation as an energy feedstock has to be carefully evaluated, and it may need economic support to be comparable with other high-yielding species dedicated to biomass production (Leible *et al.*, 2005). In this context, the use of natural grasslands for bio-conversion or heating and energy production may be restricted to areas that cannot be ploughed and in marginal environments where availability of biomass exceeds requirements for livestock feed (Peeters, 2009).

In Australia, bioenergy currently provides about 4% of Australia's total primary energy supplies and 1% of Australia's electricity, with ethanol and biodiesel providing slightly <2% of the transport fuel consumed nationally (Stucley *et al.*, 2012). Currently, most plant biomass for energy comes from sawmill and sugar mill residues and cereal straw and, to date, relatively few agricultural crops have been grown specifically as energy sources, apart from some canola used for biodiesel. However, there is the potential for purpose-grown bioenergy crops, particularly of grasses, in southern Australia (O'Connel *et al.*, 2007; Miranowski *et al.*, 2010; Farine *et al.*, 2011; Stucley *et al.*, 2012). Annual grass crops could be readily integrated into crop-pasture rotations, and producers could employ the same production tools and techniques used for hay production. However, bioenergy cropping would displace other crops or pasture and the key factor in its adoption would be its profitability, relative to grain cropping and livestock production. This in turn would be determined by the price that bioenergy plants could pay for feedstock. Analyses for grass grown in the 450–600-mm annual rainfall zone of south-western Australia suggest that the delivered cost of dried and baled grass biomass would be in the range of A$132 to A$267 per tonne, compared to A$53 to A$138 per tonne for cereal straw biomass (Stucley *et al.*, 2012). In many situations, more than 50% of the cost of producing energy from such crops can be attributed to the costs of producing, harvesting, transporting, processing and conditioning the biomass feedstock.

Globally, the breeding and selection of crops grown mainly for energy use are at an early stage of development. Little work has been conducted to date in southern Australia.

In southern Europe, the OPTIMA project (www.optimafp7.eu) is evaluating the physiological and productive responses of some native perennial grasses that are widespread in the semi-arid Mediterranean area, either for bioenergy alone or for dual-purpose forage and bioenergy use (Copani *et al.*, 2013; Porqueddu *et al.*, 2014). Preliminary results suggest *Saccharum spontaneum* L. and *Piptatherum miliaceum* (L) Coss. are the most promising grass species, showing high DM yield and a favourable biomass allocation. Previous experiments showed that conventional bioenergy species, such as *Miscanthus* × *giganteus* Andress. and *Panicum virgatum* L., need irrigation to achieve high DM yields in Mediterranean areas, while *Arundo donax* L. appears to be more drought resistant than *Miscanthus* (Cosentino *et al.*, 2007). Further genetic evaluation and agronomic work is required before economic and reliable bioenergy crop production can be considered in the Mediterranean regions.

Ecotourism

Ecotourism is a nature-based form of tourism in rural areas that are usually characterized by high species and habitat diversity, and in which the tourism experiences are managed using sustainable practices (Parente and Bovolenta, 2012). Ecotourism is often practised in areas that are very fragile in ecological, social and cultural senses. It is an important tool for the creation of additional income for farmers, especially in protected and mountainous areas. Grasslands in the Mediterranean region provide natural beauty, diversity of wildlife and recreational opportunities such as hunting, hiking, and camping, as well as economic opportunities such as ranching and mining (Louhaichi, 2011). Hunters are often willing to pay up to ten times the butcher's price for hunting a wild animal on the farm, and they often use a range of facilities and services provided by the farmer, thus contributing further to his income (Pardini, 2002). In some natural parks across the Mediterranean region, livestock are grazed to reduce the shrub cover and tree regeneration that increase the risk of wildfires (Bernués *et al.*, 2005). Joint animal grazing and tourism usage are more likely in mountainous areas where the land is of prime value for skiing, hiking and camping (Georgoudis *et al.*, 2005). If such efforts are not planned well, tourism and livestock rearing can compete with each other. Ecotourism and livestock grazing can be mutually beneficial. However, conservation policy should be directed towards incentive schemes and environmental education with technical assistance (Plieninger, 2007).

Conclusions and future directions

Despite their ecological, economic and social importance, Mediterranean grasslands receive limited scientific, political and media attention. This is because in the Old World they are widely perceived as degraded lands suitable only for grazing, while in the New World cropping is seen as a higher-value land use. However, the outcomes of these pastoral systems are farm products with special sensory and nutritive qualities, produced under the natural, year-round grazing conditions that the climate in these regions allows. The increasing global demand for high-quality animal products may see the importance of these regions increase, but this demand needs to be balanced against the need to protect these environments against erosion and loss of biodiversity, while also satisfying the interests of tourism.

Although there are pronounced socio-economic differences among the different Mediterranean regions, they share several common grassland issues. Of high importance is the need for greater adaptation to increasing drought periods and seasonal variability from predicted climate change. There is an urgent need for increased resources to be dedicated to the development of new varieties of grassland species for the Mediterranean areas. Multidisciplinary investigations are needed to identify the best-adapted and most productive grassland species, cultivars and mixtures to produce high-quality livestock products in the different regions, along with the most appropriate grazing management. Forage legumes are seen as crucial in driving productivity of grassland systems in each region. For Old World grasslands, selection among local strains is likely to identify the most promising types. However, the successful development of a pasture seed industry in the Mediterranean basin and in Chile is critical to guarantee seed supplies of the best-adapted cultivars to these regions. Long-term multidisciplinary experiments are also needed to monitor the pastoral resources, environmental outputs and ecological services associated with Mediterranean grasslands, to ensure a better understanding of the complexity of grassland ecosystems and to inform management decisions and measures for mitigation of climate change.

Finally, more on-farm experimentation and appropriate and participatory knowledge transfer to farmers are required in each region to optimize the productivity and sustainability of grassland systems. A particular focus should be on the appropriate incorporation and management of locally adapted legumes and grass–legume mixtures in the different agricultural systems, which is necessary for their full exploitation. Management and rehabilitation in the long-term should to be conducted in a participatory manner, and institutional and policy support is urgently needed, in addition to technical aspects, for the sustainability of grassland resources. Of particular concern is the decreasing public sector support for grassland research and development. This requires greater international scientific and technical cooperation among the few institutions operating in the different Mediterranean-climate areas of the World to provide innovative and sustainable solutions to farmers.

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