Appendix 2. Natural selection in southern Australian pastures under climate change: a brief review

Summary

- Evidence from experimental and modelling-based studies indicates that Australian grasslands are likely to undergo significant changes in composition and productivity this century in response to changes in temperature, precipitation and atmospheric CO_2.

- Significant levels of genetic variation are known to occur in both native and introduced pasture species in Australia.

- Variation for a range of climate-relevant traits is known to exist in a range of Australian pasture species. The extent of variation for traits associated with drought and heat tolerance is not known, except in a restricted set of introduced species such as *Phalaris aquatica* and *Lolium rigidum.*

- The heritability and potential response to selection of different climate-relevant traits is not known for any Australian native pasture species. However these traits are known to be heritable and responsive to selection in some introduced species.

- Paleobotanical evidence suggests that climate-driven evolution does not, in general, result in the broadening of species' physiological niches and that changes in species distributions broadly track changes in climate.

- Theoretical and contemporary evidence indicates that local adaptation could potentially alleviate some of the adverse effects of climate change, especially in range-core areas where plant population sizes and genetic variation are large.

- We suggest that a targeted research effort based on quantification of heritable variation for a range of traits in species representative of different key functional groups would help determine the evolutionary capacity of key pasture species, and would provide pointers for better management of southern pastures under future climate change.

In a general sense, how might pastures in Australia (both native and sown) alter under the impact of a changing climate?

Here we review the potential impacts of climate change on the Australian pastures, rangelands and grasslands. We specifically consider the roles of temperature, precipitation and elevated atmospheric CO_2 on grassland composition and structure; evolutionary and genetic components of change are specifically addressed below.

The composition and structure of Australian pastures, like grassland ecosystems globally, varies markedly in response to a wide range of factors including soil type and nutrient levels, climate, topography, disturbance regime, and the presence of invasive species. Significant changes in the composition of grasslands in southern Australia have already occurred over the past 200 years, with tall warm-season perennial tussock grasses being replaced by short cool season perennial or introduced annual species, depending on grazing intensity, fertiliser use, fire frequency, and cultivation (Moore 1970; Garden *et al.* 1995). State and transition models describing these compositional shifts (Garden & Bolger 2001) document that many Australian grasslands and pastures are prone to change when faced with altered abiotic and biotic conditions.

Several lines of evidence suggest that climate change will drive significant, broad-scale changes to Australian pastures. First, several key functional groups of grassland species show marked distributional responses to climate: for example C_3

species tend to dominate regions characterised by wet, cool springtime conditions while C_4 species (Osmond 1987) are prevalent in more warmer regions with dominant summer rainfall (Johnston 1996). Similar compositional patterns exist at smaller spatial scales (Williams 1979; Johnston 1996). Second, extreme climatic conditions such as drought are known to dramatically affect grassland species (Godfree *et al.* 2010), especially under grazing (Hutchinson 1992), while phenological change has been observed in subalpine species subjected to experimental warming (Hoffmann *et al.* 2010). Third, results from most experiments globally indicate that grassland systems undergo significant composition change when exposed to simulated climate change and CO_2 enrichment (Grime *et al.* 2000; Zavaleta *et al.* 2003) and results of pasture modelling generally support this view (e.g., Howden *et al.* 1999; although see Grime *et al.* 2008). Finally, Australian rangelands have responded significantly to past climate change events (Cupper 2005).

Predicting the specific patterns of change in most southern Australian pastures in the absence of any significant *in situ* experimental evidence remains difficult. This reflects the complex nature of interactions between water availability, precipitation, soil nutrient levels, temperature, and CO_2 concentration (Tubiello *et al.* 2007). Invasive species, disease and herbivory, also affected by climate change, may also play an important role in many systems. Furthermore, many of the expected improvements in pasture production and performance resulting from CO_2 enrichment (see below) may be offset or negated by declining rainfall, a variable that exhibits wide variability in global circulation model projections for Australia.

The most detailed investigation of the changes expected in Australian rangelands is reported by McKeon *et al.* (2009) (see also Howden *et al.* 1999). Using a model-based approach, they show that pasture production across Australia is likely to rise as a response to elevated CO_2, but decline with rising temperature and declining rainfall. Depending on the specific combination of changes to CO_2, temperature and rainfall, future pasture production estimates range from 45% below current levels to 62% higher. Realistic estimates for 2070 (650 ppm CO_2; +3°C, -10% rainfall) predict a 15% decline in productivity across Australian rangelands nationwide, but estimates are highly contingent on changes in rainfall regimes. The authors note that given the strong effects of CO_2 and rainfall on pasture performance many uncertainties remain in predicting the behaviour of rangelands in response to climate change (McKeon *et al.* 2009). However, the models presented suggest that native pastures of temperate southeastern and southwestern Australia, where soil fertility plays a more important role in limiting production, are likely to be less susceptible to climate change than semi-arid or arid rangelands, with productivity changes in the order of -10% to +10% depending on the specific climate scenario.

Little is known about the specific manner in which different pasture communities are likely to respond to climate change. In a general sense, rising atmospheric temperatures and reduced winter precipitation might be expected to increase the proportion of southern Australia that lies under subtropical influence (http://climatechangeinaustralia.com.au). Semi-arid and arid zones may also expand in some areas. C_4 species, which, being more water-use efficient than C_3 species, dominate in warmer and drier parts of Australia (Williams 1979; studies reported in Johnston 1996) would probably benefit (relatively) from declining winter rainfall and rising temperatures in cooler, wetter regions while cool-season annual and perennial species may decline. A shift towards growing subtropical species is now being advocated as far south as the central western slopes of NSW, a trend likely to continue into the future. In cooler, wetter tablelands regions local reorganisation of the dominance relationships among C_3 species is likely.

As mentioned, rising atmospheric CO_2 is likely to be a key driver of changes to many ecosystem processes. All else being equal, CO_2 enrichment is likely to increase the productivity of vegetation systems (Drake *et al.* 1997; Howden *et al.* 1999; Tubiello *et al.* 2007; McKeon et al. 2009), including grasslands and rangelands (Jongen and Jones 1998; Morgan *et al.* 2001), with growth and productivity gains likely higher in C_3 species than in C_4 species (Poorter 1993; Tubiello *et al.* 2007). However, differences between C_3 and C_4 species may be less than is often suspected (Morgan *et al.* 2001) due to the complex nature of CO_2-precipitation-temperature-soil interactions in most plant communities. Elevated atmospheric CO_2 will also probably favour increased incursion of weedy weeds and shrubs into grasslands and rangelands, because woody species have metabolic processes, carbon allocation regimes and root characteristics that are more responsive to elevated CO_2 than grasses (Morgan *et al.* 2007). Changes to carbon cycling and carbon pools (Hungate *et al.* 1997) and alteration of the responsiveness of plant species to heat and drought stress in response to CO_2 enrichment (Barker *et al.* 2005) can also be anticipated.

Finally, under climate change the frequency and severity of extreme events is also expected to increase in many parts of Australia. An increase in the severity of droughts and heatwaves would likely have a significant impact on the production and composition of Australian pastures, since recent work has shown that native grass species can be strongly affected by extreme events (Godfree *et al.* 2010). The greatest effects would most likely be evident in marginal environments where species exist towards their physiological limits (Hampe & Petit 2005), and over time, this could result in loss of species from these pastures.

Overall, the available evidence indicates that many southern Australian pastures are likely to undergo substantial compositional and structural change in response to climate change. This is not surprising, since grasslands are well known to respond in often dramatic fashion to both short – term (Godfree *et al.* 2010; Weaver & Albertson 1944) and long-term (Collatz *et al.* 1998; Cupper 2005) atmospheric conditions.

What is the evidence that genetic variation in pasture species may give them the capacity to evolve under a changing climate in a practical situation (i.e. when grazed)?

In this section we review the evidence for genetic variation in Australian pasture species and discuss the factors that underpin the capacity of species to respond to climate change via genetic advance for advantageous traits. We discuss the evidence for native and introduced pasture species separately as data availability varies greatly between the two groups.

Overview

Climate projections for southern Australia suggest that most plant species and communities in southern Australia will likely face warmer temperatures, reduced water availability (especially in winter), higher evaporation, increased transpirational demand, and an increase in the frequency and severity of heatwaves and drought. For the purposes of this section we therefore assume that the dominant selection pressure arising from climate change will be on traits linked to these stresses. However, we note that for Australian pastures, knowledge of the identity of the specific traits that are likely to be relevant to climate change remains extremely limited.

Plants can respond to climate change via evolution for advantageous traits only under the following specific circumstances. Within-population genetic variation must exist for traits that result in differential fitness of individual plants, and this genetic variation must be heritable. Selection must also act on relevant traits, resulting in increased frequency of advantageous alleles in the population, and genetic advance must occur at rates similar that of climate change itself.

Genetic variation

Native species

Presently, little information is available concerning the level of inter-population and intra-population variation for traits related to growth, water use, productivity and phenology in extant populations of native Australian pasture species. This is unfortunate given that native tussock species are keystone components of many Australian pastures, especially in broadacre grazing and rangeland assemblages. Perhaps the most well studied species has been the perennial C_3 tussock grass *Austrodanthonia caespitosa*, for which variation in phenology, reproduction and growth has been quantified in populations collected from arid to temperate environments (Hodgkinson and Quinn 1976, 1978). These studies indicate that genotypic differentiation for vernalisation response, inflorescence development rate, day length for floral initiation, optimum temperatures for growth, and growth rate is present in populations of *A. caespitosa.* This work also demonstrated significant intrapopulation variability in reproductive time, with southerly populations exhibiting greater variability.

Variation for similar traits has been observed in *Themeda australis* (Groves 1975; Evans and Knox 1969), which has a complex cytology in Australia (Hayman 1960). Other studies, however, have shown that ecotypic differentiation does not exist for germination characteristics in some populations of this species (Groves *et al*. 1982). Waters *et al.* (2003) demonstrated that significant intraspecific variation and ecotypic differentiation exists among a range of native grassland species from inland NSW and Queensland for traits such as plant height, and basal diameter, and that within-population variation was also significant in some species. In a very large study (Garden *et al.* 2005; Norton *et al.* 2005; Waters *et al.* 2005) conducted across multiple biomes in south-eastern Australia, comparisons of different genotypes within several native species including *Elymus scaber* and *Microlaena stipoides* revealed significant interpopulation-level differences in survival, recruitment and herbage production. Interestingly, however, Waters *et al.* (2005) argued that interpopulation variation in these traits may be related to genetic drift rather than local adaptation. Fine scale trait variation, ecotypic differentiation or genetic divergence has also been observed in *Microlaena stipoides* in northern NSW (Magcale-Macandong 1994), *Danthonia* spp. (Lodge & Shipp 1993) and *Poa hiemata* in the Australian Alps (Byars *et al*. 2009).

Collectively, the evidence suggests that significant interpopulation ecotypic differentiation exists in a broad range of grass species from southern and eastern Australia. Within-population variation for a range of traits associated with growth and reproduction is also known to exist in some species. This is consistent with the observation that a high proportion of Australian grasses are self-pollinating or lack self incompatibility (Groves and Whalley 2002), since in general interpopulation differentiation is expected to be higher in self-fertilising than outbreeding species. It therefore appears reasonable to conclude that at least some, and probably most native pasture species have sufficient genetic variation for evolution to act on under climate change.

Introduced species

In southern Australia, economically important introduced pasture species occur in a wide array of functional groups. Palatable, desirable species include an array of annual grasses (e.g., *Lolium rigidum*, *Bromus* spp., *Avena* spp.), perennial grasses (e.g., cocksfoot, *Phalaris*, *Lolium perenne*, *Festuca arundinacea*), and both annual and perennial legumes (e.g., *Medicago* spp., *Trifolium* spp.). Other leguminous genera have also been proposed as having grazing potential in this region (e.g., *Vicia*

spp., *Astragalus* spp.; Cocks 2001). A range of species that may be desirable in certain pasture situations also occur; these include perennial forbs (e.g., *Hypochoeris radicata*, *Plantago lanceolata*), annual forbs (*Trifolium* spp.) and perennial grasses (e.g., *Nassella neesiana*, *Eragrostis curvula*). In the case of *Plantago* and *Eragrostis*, desirable cultivars have been developed for commercialisation (Johnston 1989; Rumball *et al.* 1997). Here we briefly review evidence for genetic variation among a selection of the more important of these species.

Annual introduced grasses are known to exhibit significant genetic variation both in Australia and worldwide. For example, annual ryegrass, which is an important forage species in drier parts of southern Australia, is known to show quantitative variation for herbicide tolerance (Heap & Knight 1990), which evolves rapidly under field conditions. Variation in phenology, flower induction and dormancy release which, for an annual species, are likely to be important under climate change, have been observed in Australian accessions of *L. rigidum* (Cooper 1960; Steadman *et al.* 2003), and adaptation of *L. rigidum* to Australian climatic conditions has been observed over large spatial scales (Gill *et al.* 1996). Variation and local adaptation has also been observed for dormancy- and growth-related traits in *Bromus diandris* in southern Australia (Gill *et al.* 1984), while ecotypic differentiation has been recorded in *Avena* spp. in NSW and Queensland (Whalley & Burfitt 1972). These data indicate that introduced annual grasses in Australia are likely to exhibit significant large- and small-scale genetic variation for climate-relevant traits, thus increasing the likelihood of evolution under selection pressure.

Variation for drought-related traits is also well documented in other introduced plant groups. Drought tolerance, summer dormancy and other traits exhibit significant variation in Australian and Mediterranean accessions of *Phalaris aquatica*, *Dactylis glomerata, Lolium perenne* and *Festuca arundinaceae* (Oram 1984, Reed 1996, Piano *et al.* 2004; Norton *et al.* 2006; Culvenor 2009). Genetic and phenotypic variation has been observed for numerous traits (e.g., summer moisture stress adaptation and growth) in *Trifolium repens* (white clover; Lee *et al.* 1993; Jahufer *et al.* 1999), and also in other species including strawberry clover (McDonald 2008). Seed dormancy (hardseededness) and phenology vary in the annual species *Trifolium subterraneum* (Smetham 2003), and numerous cultivars of *Medicago polymorpha* and *Medicago truncatula* are now sown in Australia. Ecotypic or cultivar-based differentiation has also been recorded in overseas collections of *Hypochoeris radicata* (Becker *et al.* 2008) and *Plantago lanceolata* (Rumball *et al.* 1997). While far from comprehensive, these case studies suggest that many desirable introduced species in Australia are likely to exhibit significant within-and between-population variation for climate-relevant traits.

Finally, numerous introduced weedy species that severely curtail pasture production are also known to be genetically variable within Australia. Such species include *Echium plantagineum* (Paterson's curse, Piggin & Sheppard 1995), *Hypericum perforatum* (St John's wort; Campbell *et al.* 1992), *Nassella trichotoma* (serrated tussock; Hussaini *et al.* 1999), and *Nassella neesiana* (Chilean needlegrass, Britt *et al.* 2002). This is consistent with the observation that invasive species often exhibit significant genetic variation and can undergo rapid adaptation in new environments (Prentis *et al.* 2008).

Heritability and potential response to selection
Virtually no research has been conducted on the heritability and response to selection of traits relevant to climate change in any native Australian pasture species. In our opinion this is probably the single largest knowledge gap relevant to predicting the evolutionary response of Australian pastures to climate change. Indeed, the

extent of heritable variation for traits associated with water use efficiency, growth and other key physiological and demographic traits is also unknown for most introduced pasture species that have a history of breeding and adaptation in Australian agriculture.

Native species

One key problem is that Australian native grasses have little history of breeding and selection. However, lines of *Austrodanthonia richardsonii* and *A. linkii* have been commercialised based on selection for seed retention and production (Lodge & Schipp 1993). *Microlaena stipoides*, a common species in cool, wet environments, has undergone selection for morphology, flowering time and seed production. Other traits that appear to demonstrably respond to selection include cool-season leaf production and dry matter yield (in *Astrebla lappacea* and *A. pectinata*), stem height (in *Themeda australis*), and culm formation (in *Bothriochloa macra*). Breeding and selection of these and other native Australian grasses is reviewed in Lodge (1996). Response to selection for grazing tolerance, productivity and response to soil fertility has been observed on decadal scales under natural settings in *Austrodanthonia* spp. and *M. stipoides* populations (reviewed in Oram & Lodge 2003). These authors suggest that the evolutionary potential of Australian native grass populations has been frequently overlooked and that many characteristics of pasture grasses in general are as responsive to selection as those in crop or introduced pasture plants.

Introduced species

The international literature indicates that many traits potentially under selection in a changing climate exhibit heritable variation in both crop and pasture species. For example, water use efficiency has a moderately to strongly heritable basis in some populations of lucerne (Ray *et al.* 1999), cotton (Condon & Richards 1992; Stiller *et al.* 2005), tall fescue (Johnson *et al.* 2008) and crested wheatgrass (Asay *et al.* 1998). Evolutionarily important traits such as salt tolerance (Ashraf *et al.* 1986), grass seed awn length (in fire-prone systems; Garnier & Dajoz 2001), frost tolerance (Caradus *et al.* 1990), hardseededness and flowering (Ramakrishnan *et al.* 2004), and vegetative yield, seed yield, crude protein, and plant height (De Araújo & Coulman 2002) also have a significant heritable basis in different plant groups. Breeding systems and facultative allocation to cleistogamous versus chasmogamous flowers is known to be heritable (in the broad sense) in *Danthonia spicata* (Clay 1982); cleistogamy is common in Australian grasses (Campbell 1983).

Heritable variation and response to selection have been investigated in several key species within an Australian context. The ability of *Phalaris aquatica* to re-sprout from buds at the basal nodes of tillers following summer rain has been shown to have a heritable basis (Culvenor 2009), with narrow-sense heritabilities of approximately 0.4 (Oram 1984). This mechanism, which improves the ability of *Phalaris* to withstand drought, is a likely candidate for selection under climate change. Drought tolerance based on summer dormancy also appears to be responsive to selection in cocksfoot (*Dactylis glomerata*; Piano *et al.* 2004). Seed dormancy in *Lolium rigidum* is known to have a genetic component and reduced levels of dormancy can be selected for (Goggin *et al.* 2010), while evolutionary adaptation has been observed in *Trifolium subterraneum* (Nichols 2004).

Overall, these data suggest that many Australian pasture species likely possess some degree of evolutionary potential under climate change. However, this conclusion is based largely on inference as evidence for selection and evolution exists for a very few Australian pasture species. In the absence of clear experimental data obtained from Australian settings we must conclude that the rate of evolutionary

responses to climate change in different parts of species' ranges, the specific responses of Australian species, and the traits involved are not well understood.

The role of grazing

As noted above, grazing has apparently led to genetic changes in populations of native grasses in southern Australia over a relatively short timescale (Oram & Lodge 2003). On the other hand, grazing has been responsible for large-scale replacement of warm season native grasses with cool-season perennial and annual species over much of southern Australia over the past 200 years. Presumably grazing practices that adversely affect the size and reproduction of plant populations (e.g. Hodgkinson 1976) would reduce the capacity of associated species to evolve in response to climate change. Historical evidence indicates that taller, tussock-forming or caespitose grasses do not tolerate grazing as well as shorter, stoloniferous species with protected growing points (Garden & Bolger 2001), and so the former species would likely suffer relatively impaired capacity to respond to climate change via evolution. However, variation for these traits exists in some species that are potentially at risk from the effects of grazing under climate change, such as *Themeda australis* (see Oram & Lodge 2003). Management regimes that minimise grazing during reproduction may improve the evolutionary performance of such species. Grazing practises (e.g., overgrazing) that advantage less palatable or weedy species such as *Nassella trichotoma* and *Eragrostis curvula* at the expense of more palatable species could also increase both the dominance and evolutionary potential of weedy species in southern pastures. At present however the interactions between future climate change, grazing and evolution are unclear.

<u>Might pastures have the capacity to change at the same pace as the climate?</u>

Numerous studies have demonstrated that local adaptation for advantageous traits can develop in plant populations in response to changing environmental conditions on relatively short (generational) timeframes (see Bone & Farres 2001; Davis *et al.* 2005); rapid ecotypic differentiation in Australian lines of *Trifolium subterraneum* (Nichols 2004) is a case in point. Consequently, some authors argue that evolution may play a significant role in mitigating some of the adverse effects of climate change on plant populations (e.g., Davis *et al.* 2005). Indeed, evidence for rapid selection for environment-linked traits in natural plant populations (e.g., Antonovics *et al.* 1971) challenge the traditional Darwinian view that evolution is a slow process, with significant changes accruing only over long periods of time.

In a recent review, however, Gienapp *et al.* (2008) demonstrate that unambiguous experimental evidence for a clear role for microevolutionary adaptation in mitigating the negative effects of climate change remains scarce. Parmesan (2006) arrived at the same conclusion from paleophytogeographical evidence, noting that past episodes of major climate change (such as Pleiostocene glaciation) did not stimulate major evolution in plant taxa, and that most species appear to have shifted their geographic ranges to track changes in climate. Indeed, there is little evidence that the absolute physiological tolerances of species shift in response to climate change, or that novel genotypes develop that facilitate the movement of species into new climatic zones (Parmesan 2006, papers cited therein). Indeed, Huntley (2007) argues that while evolutionary advance for some phenotypic traits may occur, evolutionary adaptation is unlikely to be an important driver of species' responses to climate change in the coming century, and that habitat fragmentation and the projected speed of climate change could severely curtail what evolutionary potential does exist.

Although the debate continues, these lines of evidence collectively suggest that successful species will be restricted to those that have sufficient levels of genetic diversity to cope with rapid climate change (Huntley 2007). Evolutionary theory

suggests that this is more likely to occur in environments that are experienced by the largest number of individuals within a population (i.e., towards the centre of species' ranges) (Bridle & Vines 2006), and may be more likely in populations of introduced or invasive species, which often exhibit rapid local adaptation (Prentis *et al.* 2008). Evolutionary change in response to shifts in climate are probably less likely to occur in marginal environments where plant populations have had a long history of selection for climate-related traits and hence a narrow genetic base (Bridle & Vines 2006). In such habitats plant species may often be characterised by the ability to persist for long periods of time without recruitment, instead relying on longevity, persistent seedbanks (Hampe & Petit 2005) and probably phenotypic plasticity. These traits have been linked to a reduction in the ability of plant species to evolutionarily respond to contemporary selection regimes (Silvertown 1988). Thus, extinctions are more likely to occur when species and populations that occur in marginal environments are moved outside of their physiological niches.

<u>Potential future work</u>

As discussed above many knowledge gaps exist in the literature associated with evolutionary and ecological responses of Australian pastures and grasslands to climate change. We suggest that the key knowledge gaps that should be addressed in future work are:

1. What is the level of heritable genetic variation in native and introduced species that represent the key functional plant groups in pastures and grasslands?
2. What are the traits that are likely to be selected under climate change?
3. Do core and range-edge populations of native and introduced species differ in evolutionary potential?
4. Giving any lack of adaptive potential, which grazing systems are most likely to be placed at risk by climate change?

Here we propose a research plan that is aimed at filling these knowledge gaps as efficiently as possible. It involves 3 key stages conducted over 3 years aimed at providing a preliminary determination of the key traits selected for under climate change (warmer and drier conditions) and the extent of heritable genetic variation in these traits.

Stage 1: Identification and collection of key pasture species

Time: 12 months

Since little is known of the evolutionary potential of pasture species in Australia, the first stage of the research plan would be to identify representative species from each of the main plant functional groups in SE Australian pastures, and to then make collections of core and range-edge populations for each species. We would focus on species that crucially underpin grazing operations in this region and would span the key bioregions of southern Australia. Possible species and groups could include:

Functional group	Species	
Native perennial grass	*Bothriochloa macra* *Microlaena stipoides* *Austrostipa spp.*	*Austrodanthonia spp.* *Themeda australis*
Introduced perennial grass	*Lolium perenne* *Phalaris aquatica* *Dactylis glomerata*	*Festuca arundinacea* *Pennisetum clandestinum*
Introduced annual grass	*Hordeum leporinum* *Lolium rigidum* *Vulpia sp.*	*Bromus molliformis* *Avena barbata*
Introduced annual forb	*Trifolium subterraneum* *Medicago truncatula*	*Arctotheca calendula* *Echium plantagineum*

Functional group	Species	
Introduced perennial forb	*Medicago sativa* *Trifolium repens* *Carthamus lanatus*	*Acetosella vulgaris* *Hypochoeris radicata*
Invasive grass species	*Nassella neesiana* *Nassella trichotoma*	*Hyparrhenia hirta* *Eragrostis curvula*

These species represent many of the key, naturalised or native pasture species of southern Australia. Ideally, we would collect two range-edge and two range-core populations from each species included in the study. It would probably be practical to survey one to two of the most important species in each group, but numbers would depend on funding availability.

Stage 2: Within-population trait identification and evaluation of genetic variation

Time: 24 months

This stage quantifies the genetic variability in traits that are likely to be subjected to significant selection pressure under climate change. We think that a study aimed at identifying genetic variation for flowering time, dehydration tolerance and avoidance, water use efficiency, heat tolerance, rooting depth and resource allocation in the subset of important pasture species identified above would be an essential part of any research programme. Comparison of range-core and range-edge populations within species would provide key information on the traits that are likely to be important in a warming, drying environment.

Stage 3. Preliminary assessment of selection potential

Time: 24 months

The final stage of the work would involve initial quantification of the potential response to selection in populations of key grassland species. Species and population selection would be based on results of projects 1 and 2 above, and would include only species for which significant variation in climate-related traits was observed. Experiments would be conducted using field and/or glasshouse experiments with the objective of estimating heritability for key climate-related traits. This would address the knowledge gaps raised in this review.

Timeline & resources

As mentioned, the proposed project would run over 3 years, with overlapping of the different stages.

Research phase	Year 1		Year 2		Year 3	
Stage 1	██	██				
Stage 2		██	██	██	██	
Stage 3			██	██	██	██

The level of resourcing would depend on the number of species and functional groups chosen, the number of traits investigated, and the complexity of estimating heritability. A "first cut" approach might involve a small number of highly important species (~5-10) assessed for a restricted set of traits, and would require ~1 technical officer and modest contributions from 1-2 scientists. A comprehensive study would require 1.5-2 technical officers and significant contributions from 2-3 scientists. Operating costs would include some travel and glasshouse space, and some minor consumables.

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