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Abiotic stress tolerance of kikuyu (*Cenchrus clandestinus*) and some related grasses and potential of kikuyu for agricultural and urban environments

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Abstract. The introduction of kikuyu (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone) into Australia in 1918 has seen it become established and adapted to several geographic regions in a wide range of ecologies and environmental situations. After it naturalised to local conditions, researchers and farmers recognised the value of kikuyu in marginal and previously unproductive sites, where forage quality and quantity made this species popular with dairy farmers and pastoralists. Its versatility and prostrate, mat-forming characteristics also led to the adoption of kikuyu by local governments, homeowners and sporting organisations in urban environments as turf. Kikuyu has the ability to alleviate soil contamination and remediate soils, thus enhancing the use of previously unproductive land. However, the aggressive growth habit of the species, considered a problem in certain regions of the world, has led to a noxious weed classification in some states of the USA. This review includes information on expected changes to world agricultural and urban environments and the potential expanded role of kikuyu. The origin of kikuyu grass, genetic variability, tolerances to soil salinity and drought, and potential for genetic improvement are also discussed.

Additional keywords: genotype diversity, kikuyu grass, salt and drought tolerance, untapped breeding potential.

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Introduction

Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone) was confirmed as tetraploid with a somatic chromosome number $2n=36$ (Meredith 1955; Jauhar 1981). Kikuyu is a C_4 warm-season grass species with physical attributes and adaptive qualities that allow survival under stressed conditions, thus giving it an economic advantage in environmental reclamation strategies (FAO 2010). Morris (2009) and García *et al.* (2014) recognised the adaptive qualities of kikuyu grass in modern agricultural and urban production systems.

As the human population continues to grow, the increasing demand for food and other agricultural products will necessitate the use of more marginal land and inferior-quality treated water for food production (Pessarakli and Szabolcs 1999). Climate change will also alter production conditions and increase the incidence of extreme weather, which will limit productivity in many areas (Cullen *et al.* 2009; Bell *et al.* 2011; CSIRO and Bureau of Meteorology 2015). The severity and longevity of these weather extremes will directly affect crop growth and reduce the availability of low-cost, high-quality food for consumption (Rosenzweig *et al.* 2001).

In Australia, land use and soil–water–nutrient balance have changed significantly since 1788, as have plant populations and production outcomes (National Land and Water Resources Audit

2001; Gammage 2011). The survival and adaptation of both native and introduced plant species have changed, leading to changes in the structure and productivity of these plant communities.

The adaptive qualities of kikuyu, including nutritional and productivity advantages, can help to meet projected production shortfalls due to increasing human population (Bennett *et al.* 2013). Kikuyu is particularly well adapted to the intensely managed production systems of modern urban and agricultural ecologies.

In urban situations, kikuyu grass establishment has historically been an economical method of covering bare ground, including home lawns, recreational fields and groundcover for land reclamation. Turfed areas have evolved from a non-essential luxury item in urban systems to an essential component of daily life, thus enhancing urban recreation, leisure and sport experiences (Beard 1973; Beard and Green 1994; Casler and Duncan 2003). In addition, legislation governs land and water use in urban areas, and the building of most recreational facilities such as racetracks, golf courses and playing fields is restricted to land that has low agricultural, residential or industrial potential. Maintaining good surface quality at these facilities requires irrigation during drier periods; however, increasing demand for good quality irrigation water is making this resource increasingly scarce and therefore expensive.

Watering of turf may become unsustainable for most urban green spaces, particularly smaller sporting clubs and home lawns. Kikuyu is a good fit for these urban environments, and genetic variation for abiotic stress tolerance within the species can provide protection from climatic extremes while delivering surface quality and improved soil stabilisation to satisfy urban expectations and demands.

Kikuyu became widely used in agricultural systems in Australia following its introduction in 1918 (Fig. 1). In addition to the advantages of abiotic stress tolerance and survival mechanisms, various reports documented that well-managed kikuyu pastures in temperate and subtropical regions of eastern Australia produced on average 12 000 kg/ha of dry matter (DM) per year (Luckett *et al.* 1996; Reeves *et al.* 1996; Fulkerson *et al.* 1999; García *et al.* 2014). However, DM production up to 15 000 kg/ha with crude protein (CP) of leaves and stems of 21% and 17%, respectively, and metabolisable energy (ME) up to 7.4 MJ/kg DM can be achieved when water and nutritional inputs are well managed (García *et al.* 2014).

Heuzé *et al.* (2015a, 2015b, 2015c, 2016) compared kikuyu and other naturalised and native C₄ grass species found in Australia, and established tables of chemical composition including nutritional values. They reported that for paspalum (*Paspalum dilatatum*), Bermuda grass (*Cynodon dactylon*) and buffel grass (*Cenchrus ciliaris*), the average CP levels were 10.3%, 9.8% and 7.1% and average ME levels 18.3, 18 and 18.3 MJ/kg DM. By comparison, the native kangaroo grass (*Themeda triandra*) produced an average CP of 13.5% with average ME of 8.9 MJ/kg. Foster *et al.* (2010) examined another significant native Australian summer grass species, Australian red leg grass (*Bothriochloa macra*) and reported a CP of 8.9% and ME of 9.0 MJ/kg DM.

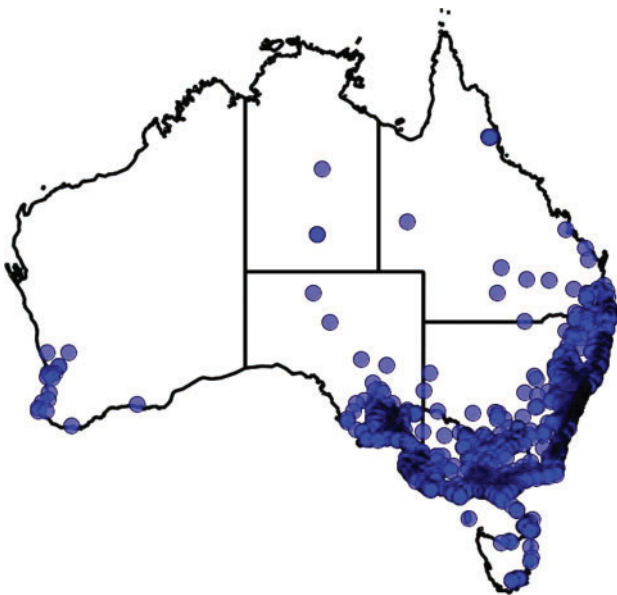


Fig. 1. Geographic distribution of *Cenchrus clandestinus* in Australia (from Atlas of Living Australia), with the most densely populated areas being the east coast in New South Wales through Victoria including an area around the river-land in South Australia (where the Murray River meets the sea); to a lesser degree, the south-west corner of Western Australia.

The CP level of kikuyu is higher than of comparable C₄ grasses, which is significant because CP is essential to animal health and is a limiting factor in the production of milk, wool and meat. As a result, kikuyu has become an important source of CP in the dairy, beef and sheep industries in Australia. Hanna *et al.* (2004) reported that kikuyu was a major pasture-grass species in the tropical highlands, cool subtropical and Mediterranean climates of the world and was the most important pasture grass species in Hawaii. Brogdan (1977) included Australia and Sri Lanka in the list of countries where kikuyu grass was a significant forage species.

This review contains information on expected changes to world agricultural and urban environments and kikuyu's potential expanded role. The origin of kikuyu grass, its genetic variability, tolerance to soil salinity and drought, and potential for genetic improvement are also discussed.

Discovery and classification

Early classification

Europeans identified kikuyu growing in an isolated tropical highland plateau of central Africa in a region occupied by the Kikuyu tribe sometime in the late 19th or early 20th Century. Emilio Chioyenda first recognised and named kikuyu in 1903 and accorded the grass the status of species (*Annuario del Reale Istituto Botanico di Roma* 1903) and chose the name *Pennisetum clandestinum* Hochst. ex Chiov. Unaware of this earlier identification, several later attempts were made to name kikuyu. However, Stapf (1921) recognised Chioyenda as the first to identify and name this species.

Modern reclassification and name change

Pennisetum clandestinum was the recognised name until Morrone *et al.* (2012), using morphology, DNA genotyping and phylogenetic analyses, reclassified *Pennisetum clandestinum* as *Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone (Chemisquy *et al.* 2010; Morrone *et al.* 2012).

For the purpose of this review, the common name 'kikuyu' or 'kikuyu grass' is adopted and *Cenchrus clandestinus* is only used if the botanical name has some relevance.

Morphological variants and genetic diversity

Natural habitat

Edwards (1940) stated that the natural habitat of kikuyu grass was limited to a comparatively restricted area at high elevation within mountainous regions of 2000–3200 m altitude with average rainfall ≥ 1016 mm/year and mean temperature 13–18°C in deep lateritic soil derived from porous lava rock. Mears (1970) reported similar highland regions in Ethiopia, Tanzania, Uganda, Rwanda and the Democratic Republic of Congo where kikuyu may also be indigenous. In light of Mears' report, all of the early material sent to Kew Gardens in England, the Royal Botanic Garden Sydney, Hawkesbury Agricultural College (now Hawkesbury Campus, Western Sydney University), the United States of America and New Zealand came from the Highlands and Lake regions of Kenya.

Early morphological evaluation

Edwards (1937) described the natural distribution of kikuyu grass and identified six primary regions and several minor regions in Kenya where this species occurs naturally.

The Edwards (1937) collection locations in Fig. 2 can be summarised as:

1. An area from Molo in the south, to north of Sergoit.
2. The ridge of highlands extending from Kikuyu through the Kinankop Plateau.
3. A region about Mt Kenya to the south and east of the mountain.
4. An area south-east of Mount Elgon.
5. An area about Kericho towards the west.
6. The upper Gilgil District lying approximately midway between areas 1 and 2.

Edwards (1937) made seven selections from the Kenyan Highlands, including five from the areas listed above. The seven ecotypes were planted at the Kabete Experimental Station for evaluation, and three lines with distinctly different morphological traits were identified. Edwards referred to these as Molo, Kabete and Rongai in recognition of the regions from which they were collected (Edwards 1937). Examples of Molo, Kabete and Rongai, sent to Australia in 1940, were planted at the Cowra Experimental Farm (now The Cowra Agricultural Research and Advisory Station—Centre for Sheep Meat Development) in central-western NSW.

Introduction in Australia

Parker (1941) reported the earliest recorded introduction of kikuyu into Australia, stating that in 1908 cuttings were sent to Edward Hawker, East Bungaree, South Australia, from the Molo district; these cuttings did not survive. A second attempt with material from Molo and Kabete was made sometime just before or after World War I; however, only the Molo cuttings survived (Parker 1941). Breakwell (1923) reported receiving kikuyu seed for identification in 1918 at the Royal Botanic Garden Sydney, from Australian quarantine. However, only one seed germinated and the resulting plant was initially referred to as carpet grass, but later reclassified as kikuyu grass. Cuttings from this plant and another vegetative form imported from Kenya were planted at the Hawkesbury Agricultural College for evaluation. It was here that the potential of kikuyu was recognised and these materials formed the basis of early trials in Australia. Plantations were subsequently established at research stations in Grafton, Wollongbar, Trangie, Cowra, Berry and Yanco.

Both Whittet (1921) and Parker (1941) recorded an early introduction in South Australia when cuttings from the New South Wales (NSW) Department of Agriculture were planted at the Waite Agricultural Research Institute. Kikuyu cuttings were also sent directly to Mr Edward Hawker from the Molo and Kabete regions in Kenya. Morris (2009) states that almost all kikuyu grass in South Australia originated from these two early introductions. The distribution of kikuyu continued through the 1920s and Whittet (1921) sent material to Victoria, most likely to the Victorian Institute for Dryland Agriculture Horsham (now Grains Innovation Park Horsham), in western Victoria (Morris

2009). During this time, vegetative materials were directly introduced from South Africa into Western Australia (Cullity 1948).

Creating named Australian cultivars

Fifteen strains imported from Kenya between 1958 and 1961 were received at the Grafton Agricultural Experimental Station (now Grafton Primary Industries Institute). Of these, one showed potential, accession number P.713 (provided by Dr AV Bogan of the Research Station Kitale, Kenya), based on vigour, winter growth and seed production (Wilson 1968). The P.713 ecotype was evaluated against other imported lines at different experimental sites and was rated as superior and subsequently registered under the name 'Whittet' in March 1970 (Barnard 1972b). Whittet is still the dominant pasture seed cultivar sold in Australia 47 years after registration.

In 1965, a phenotypic variant was discovered in the lawn at the Grafton Agricultural Experiment Station (now NSW Department of Primary Industries Institute Grafton) and seed collected for evaluation. The ensuing population produced both male sterile and fully fertile forms. Barnard (1972a) reported that this line had a fine leaf and a dense prostrate habit, characteristics deemed suitable for urban environments and erosion control. The line was subsequently registered and released in November 1971 under the name 'Breakwell'.

In 1972, a kikuyu grass found growing at the University of Sydney's farm at Camden by HJ Geddes was evaluated in experiments extending from Taree to Bega in NSW, and significant cold tolerance and superior productivity observed (Barnard 1983a). This fully fertile pasture line was subsequently registered as 'Crofts' in January 1983.

Following the discovery of kikuyu yellows disease (*Verrucalvus flavofaciens*), work commenced at Grafton to breed a resistant cultivar. A population developed by crossing Whittet with Breakwell showed resistance and was registered as 'Noonan' in March 1983 (Barnard 1983b).

Genetic diversity

The naturalised populations of kikuyu in Australia have significant genetic differences between the collected ecotypes and cultivars (Holton *et al.* 2007; Morris 2009). Holton *et al.* (2007) studied material from northern and south-eastern Queensland, north-eastern and central NSW, Victoria and the south of Western Australia (Table 1) by using DNA amplified fingerprints (DFA) as described by Caetano-Anollés *et al.* (1991) with four oligonucleotide primers and 40 polymorphic loci. Genetic diversity was determined by using polyacrylamide gel electrophoresis. Genetic relatedness was analysed by using PHYLIP as described by Felsenstein (2005) and a dendrogram created to visualise relationships (Fig. 3).

By contrast, the collections of Morris (2009) came from different areas of eastern Australia including southern Queensland, NSW, Victoria, Tasmania, South Australia, and the Australian Capital Territory (ACT) (Table 2). Morris (2009) used randomly amplified polymorphic DNA (RAPD) markers as described by Williams *et al.* (1990) to identify genetic variants in kikuyu and found 195 markers from 13 informative primers, concluding that the genetic diversity in

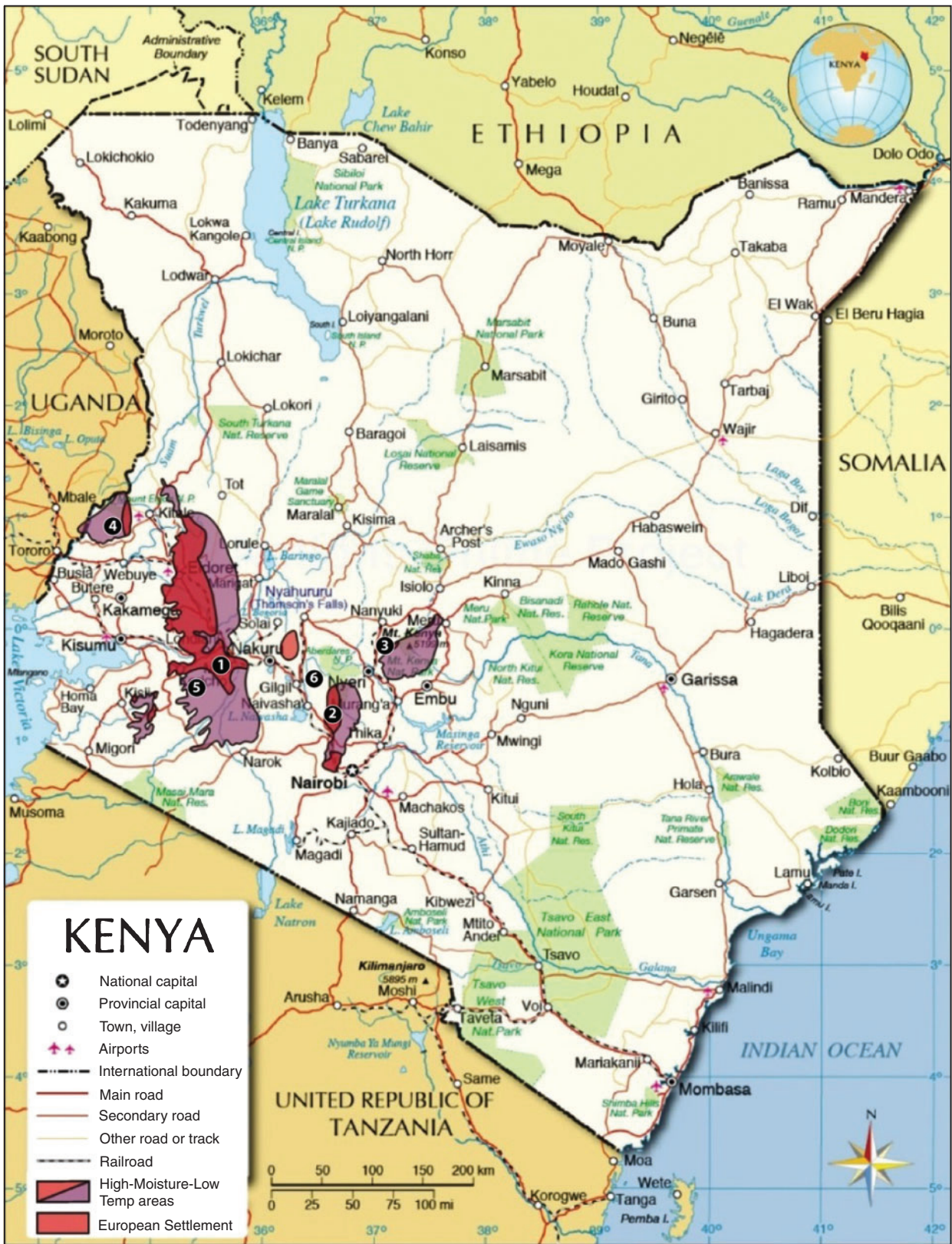


Fig. 2. The map of Edwards (1937) has been overlaid on a map of Kenya (www.nationsonline.org/oneworld/kenya.htm); coloured areas refer to regions of high moisture and low temperature where kikuyu naturally occurs; red areas indicate European settlements at the time. Map numbers relate to the Edwards collection (see text).

Australian materials derived from African imports. Genetic relatedness was then determined using the UPGMA analyses described by Sokal and Michener (1958) to construct a dendrogram (Fig. 4). Morris found three major groupings of genotypes, which was significant given the later findings of Khumalo (2015), who studied a kikuyu collection at the Döhne Research Station, Eastern Cape, South Africa, that included plant material imported from New Zealand in 1998. Khumalo (2015) also reported three major groups of materials although did not present a dendrogram of these relationships.

When comparing the dendrograms of Holton *et al.* (2007) and Morris (2009) (Figs 3 and 4), the significance of the widely grown cultivar Whittet, present in the C1 groupings (KC1100 in Fig. 4) and co-located with the cultivar Crofts, which is also represented in both analyses (KC903 in Fig. 4), becomes apparent. However, Noonan (a cross between Whittet and Breakwell) is the exception. The vegetative examples of Noonan from the Wollongbar Agricultural Research Station

(now Wollongbar Primary Industries Institute) analysed by Holton *et al.* (2007) grouped with Whittet, which originated from Kenya. However, the Noonan seed from AusPGRIS located in C3 of the Morris (2009) study grouped with Breakwell and material from Tanzania.

In the Holton *et al.* (2007) C2 grouping, ecotypes from Western Australia, Victoria, south-eastern Queensland, Wollongbar in northern NSW and South Australia are represented. The Morris (2009) C2 genotypes have unknown parentage but grouped with the Berambing accession (KC950) derived from plants grown at the Hawkesbury Agricultural College that originated from seed introduced in 1918 and was subsequently collected in cooler regions of NSW, ACT and Tasmania. These initial genotyping studies appear to identify a Kenyan origin group, a Tanzanian group, and a cooler season group centred in southern NSW.

Table 1. Australian kikuyu lines used to construct the dendrogram in Fig. 2 (Holton *et al.* 2007)

Lines and cultivars	Geographic source, Australian regions
<i>C1 grouping</i>	
Noonan	Wollongbar, northern New South Wales
Whittet	Wollongbar
Cultivar A	Wollongbar
Gympie	South-east Queensland
Noonan (Bonalbo)	Central New South Wales
Atherton Tablelands	North Queensland
Beechmont	South-east Queensland
Crofts (Bonalbo)	Central New South Wales
Cultivar B	Wollongbar
<i>C2 grouping</i>	
Wollongbar	Wollongbar
West Australian	
Victorian	
Numinbah Valley	South east Queensland
Mt Mee	Mt Mee, South east Queensland
South Australian	

Tolerances to physiological drought caused by soil salinity

Salt-affected areas of Australia and globally

Saline soils are a major global problem; inorganic ions in these soils reduce vegetative vigour and plant growth and health, thus limiting production (Pessaraki and Szabolcs 1999). Saline soils cover ~954.8 Mha globally and are present on every continent (Table 3) (Pessaraki and Szabolcs 1999; FAO 2017). Approximately 12% of global land area is suitable for agriculture, equating to 1.5 billion ha; however, much of this land is forested, protected as wilderness or in urban use (FAO 2013). Much of this arable land is limited by salinity, with some estimates suggesting that 20% of irrigated land and 2% of dryland agriculture is affected (Munns 2005).

Environmental salinity is increasing with the ever-increasing needs of human populations, and the replacement of deep-rooted perennial species with shallow-rooted introduced food crops in Australia has caused a rise in the water table, resulting in the accumulation of surface salt in some areas (National Land and Water Resources Audit 2000; Barrett-Lennard 2002; Barrett-Lennard *et al.* 2003; Rogers *et al.* 2005). The clearing of large tracts of land to establish European-style farming practices upset

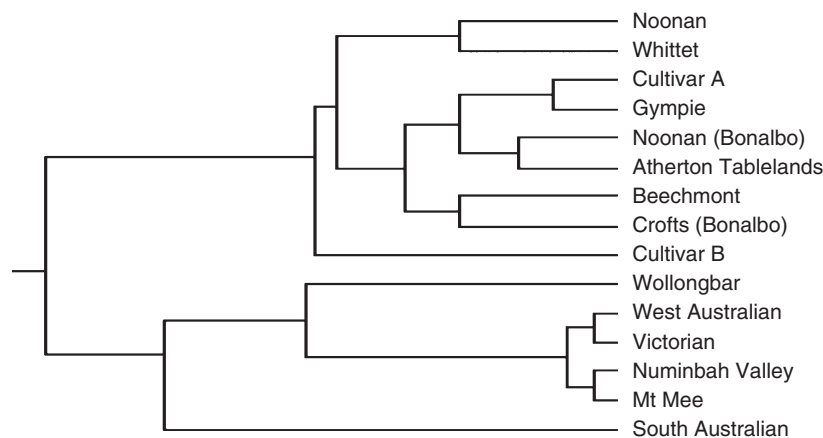


Fig. 3. Dendrogram based on DNA profiles of naturalised kikuyu ecotypes showing genetic variability among collected lines and known cultivars (Holton *et al.* 2007).

Table 2. Australian kikuyu grass lines used to construct the dendrogram in Fig. 3 (Morris 2009)

FF, Fully fertile; MS, male sterile. For description of source: a, Wollongbar Agricultural Research Station, NSW Department of Primary Industry; b, propagated vegetatively from a PBI-selected single seedling of commercial Whittet seed supplied by Eykamp Kikuyu Co.; c, a cross-section of the original collected lines

Lines	Sexuality		Propagation method and source	
<i>C1 grouping</i>				
KC1100	FF	Seed	Single seedling selection PBI	bc
KC1099	FF	Vegetative	Selection from PBI lawns, Cobbitty	c
KC966	FF	Vegetative	Selection from Cranbourne, Vic.	c
KC903 (Crofts)	FF	Vegetative	Selection USYD Farms, Cobbitty	c
KC932	FF	Vegetative	Selection from Weipa, Qld	c
KC900	FF	Vegetative	Chemical mutagenesis of Whittet	ac
KC901	FF	Vegetative	Chemical mutagenesis of Whittet	ac
KC902	FF	Vegetative	Chemical mutagenesis of Whittet	ac
<i>C2 grouping</i>				
KC945	MS	Vegetative	Selection from Tathra, NSW	c
KC924	MS	Vegetative	Selection from Canberra, ACT	c
KC950	FF	Vegetative	Selection from Berambing, NSW	c
KC934	FF	Vegetative	Selection from Stanley, Tas.	c
KC941	FF	Vegetative	Selection from Numbugga, NSW	c
KC965	FF	Vegetative	Selection from Grafton, NSW	c
<i>C3 grouping</i>				
RWS-267	FF	Seed	AusPGRIS from Tanzania	
SPA-5	FF	Seed	AusPGRIS Australian, location unknown	
Noonan	FF	Seed	AusPGRIS	
Breakwell	FF	Seed	AusPGRIS	
KC930	FF	Vegetative	Selection from Morphettville, S. Aust.	

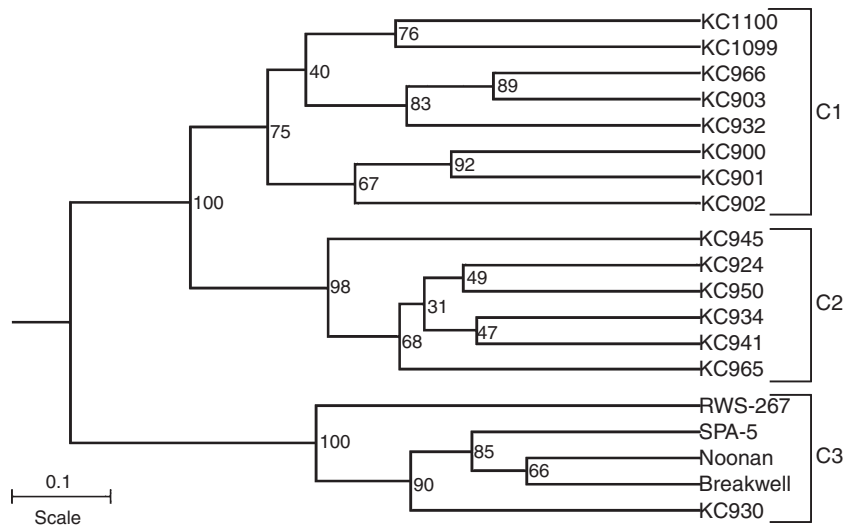


Fig. 4. Dendrogram based on DNA profiles of a cross-section of the kikuyu collection at the University of Sydney showing the genetic variability among collected lines and known cultivars (Morris 2009).

the balance created by indigenous populations before 1770 and European colonisation (Gammage 2011).

Salinity in Australia affects an estimated 465 000 ha of agricultural land, which equates to annual losses in agricultural production of AU\$251 million (Munns 2005). The National Land and Water Resources Audit (2000) report predicts that by 2020 an area of 6.37 Mha will be affected if nothing is

done to limit salt encroachment, and the area affected may climb to 13.66 Mha by 2050.

Evidence of salinity tolerance in kikuyu

When compiling a list of grasses and their relative salinity tolerances, Carrow and Duncan (2012) ranked both cool- and

Table 3. Salt-affected soils in different regions globally (Pessarakli and Szabolcs 1999)

Continent or region	Area (Mha)
North America	15.7
Mexico and Central America	2.0
South America	129.2
Africa	80.5
South Asia	87.6
North and Central Asia	211.7
South-East Asia	20.0
Australia	357.3
Europe	50.8
Total	954.8

warm-season grass species from very sensitive to very tolerant and concluded that grass species with a very high tolerance to salinity included seashore paspalum (*Paspalum vaginatum* Swartz) and alkaligrass (*Puccinella* spp.). The tolerant range included four species: kikuyu (*Cenchrus clandestinus*), salt grass (*Distichlis stricta*), fairway wheat grass (*Agropyron cristatum*) and western wheat grass (*Agropyron smithii*).

Kikuyu was tolerant to saline conditions and survived in the range 6.1–10 dS/m in solution (Carrow and Duncan 1998, 2012). Radhakrishnan *et al.* (2006) found that kikuyu tolerated moderate levels of salinity over time, with little or no detrimental effect on biomass. Russell (1976) conducted salt tolerance experiments on 11 grass species and ranked their dry matter yield. The highest zero-yield salinity concentration was observed in coolah grass (*Panicum coloratum*) and the highest half-yield for Rhodes grass (*Chloris gayana*). Nevertheless, five grasses showed potential tolerance to salinity in the experiment, including Rhodes grass (*Chloris gayana*), kikuyu (*Cenchrus clandestinus*), Columbus grass (*Sorghum almum*), Coolah grass (*Panicum coloratum*) and pangola grass (*Digitaria decumbens*).

Osmotic adjustment and biochemical tolerances of kikuyu

Muscolo *et al.* (2003) observed that the response of kikuyu to physiological drought caused by soil salinity was a function of biochemical reactions, including antioxidant defence mechanisms, within cells that induce tolerance and this was under genetic control. Muscolo *et al.* (2003) concluded that plant cells required osmotic adjustment to maintain turgor in the presence of increased salinity. Those authors found that kikuyu grass tolerates NaCl levels up to 10 dS/m in solution, with little to no detrimental effect. However, at salt concentrations >10 dS/m there were significant reductions in root and leaf biomass. At higher concentrations, up to 15 dS/m, reductions of 30% were observed compared with the control. At 20 dS/m, dramatic reductions in growth occurred from senescence caused by high leaf ionic concentrations. In a later study, Muscolo *et al.* (2013) confirmed these findings and reported that the reduction in biomass at higher salinity levels and the percentage of protein and crude fibre did not vary. Muscolo *et al.* (2013) also summarised the findings of Robinson *et al.* (2004) and Masters *et al.* (2007), who conducted irrigated glasshouse trials at NaCl levels of 15 and 25 dS/m in solution. They reported DM production equivalent to 7.8 t/ha per year with no loss in feed value up to 21 dS/m.

Radhakrishnan *et al.* (2006) investigated the potential of kikuyu to recolonise, utilise and stabilise unproductive saline areas. The authors considered several plant responses including physical biomass production and biochemical adjustments that increase osmolyte protectants, thus allowing close-to-normal plant function. They concluded that the most critical concentration, where root:shoot ratio was significantly reduced, was NaCl at 24 dS/m, following partial death of the population. In addition, a 4-fold increase in proline concentration was observed in the cells of plants in the 24 dS/m treatment compared with 8 dS/m.

Role of grasses in land reclamation and reconstitution

Previously unproductive land can be reclaimed by planting grasses. An example is the reclamation of heavy clay, saline and sodic soils in the Manzala Lake region of Egypt (Helalia *et al.* 1992). In that region, the traditional methods of soil amelioration, i.e. leaching ponds and gypsum, were compared when establishing amshot grass (*Echinochloa stagninum*), a native species that grows naturally in the drainage channels and swamps of northern Egypt. Amshot grass reduced salinity to 33.6% of the initial level, compared with 55% and 47% for ponding and gypsum, respectively (Helalia *et al.* 1992).

In the same area around Manzala Lake, Ghaly (2002) reported results from trials of two other grass species; ghab (*Phragmites communis*) and nisela (*Panicum repens*). Reductions in salinity in the top 50 cm of soil of 26.8–47%, 30.3–45.6%, 23.6–42.2%, and 21.2–35.9% were observed from ponding, gypsum, ghab grass and nisela grass, respectively. In the second year, a mix of nisela + gypsum was evaluated and salt concentrations fell to as little as 5.5–5.9% of the initial reading.

These grasses have a dual role in soil reclamation and fodder production for livestock. During the hot summer months, the heavy clay salt-sodic soils are unproductive and these species fill the production shortfall during this time, thus increasing the profitability of the region (Ghaly 2002).

Flowers *et al.* (2010) claimed that ~8.1% of halophytic species belong to the family *Poaceae*. Liphshitz and Waisel (1974), Marcum (1999) and Roy and Chakraborty (2014) investigated salt-tolerant grasses and identified specific modes of action. They concluded that tolerance was due to compartmentalisation of Na⁺ and ion exclusion, and that modified bicellular epidermal leaf cells with bio-protectant qualities exclude salt. They compiled a list of genera that have these modified cells including; *Aeluropus*, *Crypsis*, *Dinebra*, *Spartina*, *Tetrapogon*, *Bouteloua*, *Cynodon*, *Sporobolus* and *Buchloe*. Roy and Chakraborty (2014) concluded that *Pennisetum* compartmentalised ions in vacuoles that limited the toxic effect of salt. They concluded that *Leymus*, *Paspalum* and *Porteresia* use osmolyte accumulation and *Chloris* enhanced reactive oxygen species scavenging enzymes to limit the effects of salinity.

Rogers *et al.* (2005) reported that 19 grass genera, both C₃ and C₄, had potential salt tolerance. They compiled a list of salt-tolerant grasses comprising *Aeluropus*, *Cenchrus* (specifically kikuyu), *Chloris*, *Cynodon*, *Dactyloctenium*, *Distichlis*, *Enteropogon*, *Eragrostis*, *Festuca*, *Lachnagrostis*, *Leptochloa*, *Paspalum*, *Porteresia*, *Puccinellia*, *Saccharum*, *Sporobolus*, *Stenotaphrum*, *Thinopyrum* and *Zoysia*, and concluded that the

physiological characteristics of each genus should be considered before evaluating these materials in salt-affected areas. Russell and Webb (1976) concluded that economic and climatic factors govern the decision to apply ameliorates to improve soils in arid and semi-arid regions; this also applies to sowing grass species for remediation, and the risk of failure must be considered before establishing these approaches. Nevertheless, the DM value of kikuyu and its intermediate levels of salt tolerance suggest that similar remediation strategies could work in Australia.

Halophytic turf grass species

Environmental stewardship is a factor in the establishment and maintenance of green spaces in urban environments. Turf grass is an integral part of these green spaces, where recreational functionality and aesthetic beauty have an impact on human health and wellbeing (Beard and Green 1994). Turf species are different from other grasses in their mat-forming habit and survival adaptations. They must resist constant harvesting with little to no detrimental effect on survival (Beard 1973).

In addition to the challenge of high quality turf surface, irrigation is required for intense growth and production in turf systems (Carrow and Duncan 1998). Good-quality irrigation water may become unavailable or so expensive in some areas that it will be out of reach for most sporting clubs and homeowners. The use of tolerant halophytic turf species in urban scapes will allow the use of second-grade processed water for irrigation, thus utilising a previously unproductive resource to produce 'A-grade' surfaces for recreation. Turf grass species such as seashore rush grass (*Sporobolus virginicus*), seashore paspalum (*Paspalum vaginatum*), seashore salt grass (*Distichlis spicata*), and glycophyte grasses such as kikuyu (*Cenchrus clandestinus*) and couch grass (*Cynodon dactylon*) may provide a solution. The nutrient-rich treated irrigation water can be utilised by these species, thus alleviating any downstream ecological impacts of excess nutrient (Rumman 2011).

Tolerance to environmental drought caused by climate

Drought

Physical adaptations control survival of vascular plants in drier environments. An array of different mechanisms helps to withstand environmental drought and these are dependent upon the regional ecology (Turner 1999). The survival of plant populations in arid and semi-arid regions is a function of the mix of genera and their diversity, and drought tolerance is likely multi-genic and complex (Morgan and Condon 1986). More recently, Valliyodan and Nguyen (2006) reported that several stress-inducible genes and transcription factors regulate plant response to environmental drought. Other authors suggest that tolerance to abiotic stresses is activated by diverse physiological, metabolic and defence systems (Carrow and Duncan 1998; Turner 1999; Fitter and Hay 2002). Carrow and Duncan (1998) identified two quite different drought control mechanisms: (i) cascading signals under transcriptional control; and (ii) protectants that prevent the injury of cell membranes including osmoprotectants, antioxidants and reactive oxygen scavengers, all of which are under genetic control.

The significance of kikuyu in drier climates

Australia is the driest continent on Earth, with >70% of the landmass considered semi-arid to arid and some areas receive little to no rain (Wolfe 2009). In an article published in *The Agricultural Gazette of NSW* on 2 May 1921 entitled, 'A promising introduction', Whittet (1921) reported that kikuyu showed promise when commenting on the drought tolerance of the species. Similarly, the Department of Agriculture of South Africa observed that the drought resistance of kikuyu grass was high and superior to other species (Whittet 1921). When the South African veldt was dry, kikuyu remained green. Similar observations were made in South Australia and NSW (Breakwell 1923). Kikuyu has an extensive root system that can source water and nutrients from as deep as 5.5 m (Skerman and Riveros 1990). Those authors also observed that 90% of the total root-mass of kikuyu tends to be found in the 0–60 cm layer and that kikuyu was able to extract moisture from the top 1.2 m of soil up to wilting point, although growth rates declined as moisture was exhausted. Mears (1970) observed that the ability of kikuyu to utilise stored soil moisture mitigates the effect of drought and that up to 60% of the total water used was extracted from the top 60 cm of the soil.

Australian climatic zones influence plant populations and species distribution (Wolfe 2009), and the effect of drought outside the arid and semi-arid zones is region- and season-specific.

Kikuyu does have adaptive and survival mechanisms to drought including:

1. An extensive root system to source nutrients and moisture from deep in the soil profile (Skerman and Riveros 1990).
2. Biochemical protectants that reduce the effect of toxic osmolytes and inorganic ions (Radhakrishnan *et al.* 2006).
3. Seed viability and longevity of up to 10 years that allows recolonisation of pastures after extended dry periods (Helfgott 1994).
4. Micro-buds formed in leaf axis of rhizomes and stolons that are more drought-hardy than growing adult leaf material. If these buds survive, they germinate when conditions are favourable (Morris 2009; D. Fraser, pers. obs.).

The potential for breeding better adapted kikuyu

Kikuyu has one major seed-set per year in late spring or early summer, although there is a second, less prolific and somewhat opportunistic flowering in autumn (Morris 2009). Carr and Ng (1956) postulated that kikuyu flowering was controlled by auxin in undefoliated growing tips. Marais (2001) suggested that this sensitivity to auxin is genetically controlled, and varieties such as Whittet (a registered pasture genotype) were less sensitive and therefore flowered readily. Defoliation stimulates flowering when environmental conditions are optimal, although Youngner (1961) and Morris (2009) reported plants flowering on mature, uncut stands.

Kikuyu is an open-pollinated, monoecious species with both male sterile and fully fertile populations. There is some evidence of apomixis in *Cenchrus clandestinus* (Hanna *et al.* 2004); however, fully fertile forms are also reported (Brogdan 1977). Hanselka *et al.* (2004) and Narayan (1955) found that populations of male sterile kikuyu failed to produce seed when isolated from

fully fertile lines. Flowering occurs on short shoots in axils, and spikes are mostly reduced to a cluster of 2–4 spikelets enclosed in a leaf sheath and bisexual or functionally unisexual, 10–20 mm long and glabrous (Meredith 1955; Wheeler *et al.* 2002; FAO 2010). Morris (2009) reported that flowering was controlled by plant maturity and seasonal environmental factors and that fertilisation occurs over a 2–3-day period. However, Youngner (1961) observed that kikuyu stigma receptiveness dropped significantly with time, reporting a day 1 fertilisation rate of 78–89% compared with 8–23% on day 2. After fertilisation, the seed requires 2–3 months to mature—any less time and seeds do not germinate (Morris 2009). Kikuyu seeds are small at 40 000/kg (FAO 2010) and seed longevity in the field is close to 10 years (Helfgott 1994). Seed production is relatively efficient with 200–500 kg/ha recorded in Australia (Ross 1999; FAO 2010).

Morris (2009) outlined a method for breeding kikuyu that enabled the production of 1800 hybrids over a 2-year period. Stamens of selected breeding populations collected in the early morning were placed in covered Petri dishes (the author noted that kikuyu pollen loses viability significantly within the first 3–4 h after dehiscence). The pollen was separated from the anthers by taping the Petri dish on a bench and the collected pollen introduced to the stigma of the selected female line by using a small camelhair brush.

The efficacy of breeding kikuyu for tolerance to abiotic stress was limited by the available genetic diversity and potential yield and quality of the final product (Wolfe 2009). However, plasticity exists within kikuyu populations and the potential for genetic improvement of adaptation for modern agricultural and urban systems remains unexploited in modern breeding programs (Morris 2009).

Kikuyu is reportedly a glycophyte species and does not have the ability of other halophytic species to excrete or exclude salt; instead, the toxic effect is compartmentalised (Roy and Chakraborty 2014). Tolerant grass species provide fodder, contribute to land rehabilitation and utilise shallow groundwater while at the same time reducing salinity. The nutritional stability of kikuyu was significant at higher salt concentrations (up to 21 dS/m), and thus this species provides a nutritious feed source (Robinson *et al.* 2004; Masters *et al.* 2007).

Sanderman *et al.* (2013) observed increased soil organic carbon when kikuyu was introduced into production systems and reported additional rehabilitation advantages. Kikuyu provides mulch and increases carbon deposits in the upper soil horizon. The breakdown of organic matter has a positive effect on soil structure, improving both non-wetting sands and heavy clay soils.

Morris (2009) collected germplasm from tidal swamps, nutrient-depleted acid soils, areas with dry climatic conditions and numerous other extreme environments and found untapped phenotypic and genotypic diversity, identifying great breeding potential. He reported that no significant recent research into the potential of kikuyu for cultivation under stress conditions has been conducted (Morris 2007, 2009). Genetic variation for salinity tolerance within kikuyu was relatively high, although the ability of coastal lines to withstand levels >10 dS/m requires investigation.

Kikuyu is in a separate arm of the *Pennisetum*, *Cenchrus*, and *Odontelytrum* clade (Chemisquy *et al.* 2010). Bennett *et al.* (2013) studied the phylogenetic distribution of salt tolerance across the grass family based on the phylogeny of 2684 grasses from 800 different genera and concluded that tolerance to salt evolved over 70 times on several different lineages. Most of these tolerances occurred close to the tips of the phylogeny derived from diverse lineage within families rather than specific species origin.

There is potential to cross accessions within the *Cenchrus* genus, facilitated by using embryo rescue and tissue culture, to introduce broader genetic diversity for drought tolerance into the kikuyu gene pool. Buffel grass (*Cenchrus ciliaris*) is significantly more tolerant to environmental drought than is kikuyu, surviving in areas with 300 mm rainfall per annum. Buffel grass has also become naturalised in Australia following its introduction by Afghan cameleers in the late 19th Century (Humphreys 1967). This species occurs naturally in northern Africa, the Middle East, India and Indonesia. Buffel grass was not a significant species in Australia until reintroduced by pastoralists in the 1960s. The CSIRO introduced new cultivars in the 1970s to improve pasture productivity in rangelands. Significant genetic diversity exists in the *Cenchrus* and *Pennisetum* clade for tolerance to environmental stresses, available for manipulation in plant breeding to increase productivity and even extend production boundaries.

General discussion

Kikuyu production is limited by nutritional, geographic and climatic conditions and although significant genetic variation for adaptation to abiotic stresses is apparent, biotic constraints limit its potential. Abiotic stresses such as soil salinity, drought and low light intensity, exacerbated by climate variability, restrict DM production within kikuyu populations. However, Muscolo *et al.* (2013) observed that reduction in DM production had little impact on feed quality in stressed plants except in extreme cases.

Kikuyu is considered a weed in some regions of the world owing to its aggressive nature. Nevertheless, this very aggressiveness and weedy nature suggests untapped potential for survival outside the normal production zones and that genetic improvement could limit the less desirable characteristics in these environments. For example, Wilen and Holt (1996) reported that kikuyu was particularly successful in Mediterranean climates of the USA, well outside its natural adaptation, where cool night temperatures limit the production of other C₄ grasses and spring and summer rainfall is common.

However, adaptations and management will ultimately govern the success of kikuyu grass. The potential of kikuyu to satisfy the needs of pastoralists and turf managers in the 21st Century has been only partially explored and further investigation is required.

Conclusion

Pasture and turf grasses have the potential to satisfy the requirements of both urban and rural communities as competition for water resources increases. Pasture and turf grasses can have a significant future role in food productivity and in land reclamation and reconstitution. Kikuyu currently tolerates 10 dS/m of salt in solution without significant reduction in DM production and/or

percentage feed value. It can grow successfully in regions with >600 mm of rainfall. Sufficient genetic diversity for tolerance to both salinity and drought exists within the kikuyu and related gene pools to push the limits of adaptation even further.

If breeding can improve the adaptation of kikuyu to stress, then the impact of this species in urban and pastoral systems will be significant. Homeowners and sporting organisations can use these more tolerant derivatives to achieve surface aesthetics and improved playability with less frequent irrigation and with lower grade water.

Pastoralists will also benefit from more stress-tolerant cultivars through increases in productivity on existing farmland and the possible expansion of pastures into more marginal environments, thus bringing previously unproductive land into production—both an economic and a social advantage.

References

- Atlas of Living Australia. *Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone. NCRIS, Australian Government, Canberra, ACT. Available at: <http://bie.ala.org.au/species/http://id.biodiversity.org.au/node/apni/29021245> (accessed 10 March 2017).
- Barnard C (1972a) *Pennisetum clandestinum* Hochst. ex. Chiov. (kikuyu grass) cv. Breakwell. In 'Register of Australian herbage plant cultivars'. 2nd edn (CSIRO: Melbourne)
- Barnard C (1972b) *Pennisetum clandestinum* Hochst. ex. Chiov. (kikuyu grass) cv. Whittett. In 'Register of Australian herbage plant cultivars'. 2nd edn (CSIRO: Melbourne)
- Barnard C (1983a) *Pennisetum clandestinum* Hochst. ex. Chiov. (kikuyu grass) cv. Crofts. *Journal of the Australian Institute of Agricultural Science* **49**, 236–238.
- Barnard C (1983b) *Pennisetum clandestinum* Hochst. ex. Chiov. (kikuyu grass) cv. Noonan. *Journal of the Australian Institute of Agricultural Science* **49**, 238–239.
- Barrett-Lennard EG (2002) Restoration of saline land through revegetation. *Agricultural Water Management* **53**, 213–226. doi:10.1016/S0378-3774(01)00166-4
- Barrett-Lennard EG, Malcolm CV, Bathgate A (2003) 'Saltland pasture in Australia. A practical guide.' 2nd edn. Land, Water & Wool Sustainable Grazing on Saline Lands Sub-program 1. (Land & Water Australia: Canberra, ACT)
- Beard JB (1973) 'Turfgrass science and culture.' (Prentice Hall: Upper Saddle River, NJ, USA)
- Beard JB, Green RL (1994) The role of turfgrass in environmental protection and their benefits to humans. *Journal of Environmental Quality* **23**, 452–460. doi:10.2134/jeq1994.00472425002300030007x
- Bell MJ, Cullen BR, Eckard RJ (2011) The production of perennial ryegrass and kikuyu pastures in south-eastern Australia under warmer and drier future climate scenarios. In 'MODSIM2011. Proceedings 19th International Congress on Modelling and Simulation'. 12–14 December 2011, Perth, W. Aust. (Eds F Chan, D Marinova, RS Anderssen) (The Modelling and Simulation Society of Australia and New Zealand Inc.)
- Bennett TH, Flowers TJ, Bromham L (2013) Repeated evolution of salt tolerance in grass. *Biology Letters* **9**, 9. doi:10.1098/rsbl.2013.0029
- Breakwell E (1923) Kikuyu grass (*Pennisetum clandestinum*). In 'The grasses and fodder plants of New South Wales'. pp. 95–100. (Alfred James Kent, Government Printers: Sydney)
- Brogdan AV (1977) 'Tropical pasture and fodder plants.' pp. 222–231. (Longman Inc.: New York)
- Caetano-Anollés G, Bassam BJ, Gresshoff PM (1991) DNA amplification fingerprinting using very short arbitrary oligonucleotide primers. *Biotechnology* **9**, 553–557. doi:10.1038/nbt0691-553
- Carr DJ, Ng EK (1956) Experimental induction of flower formation in kikuyu grass (*Pennisetum clandestinum* Hochst. ex Chiov.). *Australian Journal of Agricultural Research* **7**, 1–6. doi:10.1071/AR9560001
- Carrow RN, Duncan RR (1998) 'Salt-affected turfgrass sites: assessment and management.' (John Wiley & Sons: Hoboken, NJ, USA)
- Carrow RN, Duncan RR (2012) 'Best management practices for saline and sodic turf grass soils.' (CRC Press: Boca Raton, FL, USA)
- Casler MD, Duncan RR (2003) 'Turfgrass genetics, and breeding'. (John Wiley & Sons, Inc.: Hoboken, NJ, USA)
- Chemisquy AM, Guissani LM, Scataglini MA, Kellogg EA, Morrone O (2010) Phylogenetic studies favour the unification of *Pennisetum*, *Cenchrus* and *Odontelytrum* (poaceae): a combined nuclear, plastid and morphological analysis, and nomenclatural combinations in *Cenchrus*. *Annals of Botany* **106**, 107–130. doi:10.1093/aob/mcq090
- CSIRO, Bureau of Meteorology (2015) 'Climate change in Australia (technical report).' (Department of the Environment, Australian Government: Canberra, ACT)
- Cullen BR, Johnson IR, Eckard RJ, Lodge GM, Walker RG, Rawnsley RP, McCaskill MR (2009) Climate change effects on pasture systems in south eastern Australia. *Crop & Pasture Science* **60**, 933–942. doi:10.1071/CP09019
- Cullity M (1948) Kikuyu grass. *Journal of the Department of Agriculture of Western Australia* **25**, 185–198.
- Edwards DC (1937) Three ecotypes of *Pennisetum clandestinum*. *Empire Journal of Experimental Agriculture* **5**, 317–377.
- Edwards DC (1940) The reaction of kikuyu grass (*Pennisetum clandestinum*) herbage to management. *Empire Journal of Experimental Agriculture* **8**, 101–110.
- FAO (2010) FAO, Rome. Available at: <http://www.fao.org/AGP/AGPC/doc/GBASE/DATA/PF000298.HTM> (accessed June 2016).
- FAO (2013) 'World statistical yearbook.' (FAO: Rome)
- FAO (2017) Global network on integrated soil management for sustainable use of salt affected soils. Natural Resources and Environment, FAO, Rome. Available at: www.fao.org/ag/AGL/agII/spush/intro.htm (accessed June 2016)
- Felsenstein J (2005) 'PHYLIP phylogeny inference package (version 3.6).' (Department of Genome Science, University of Washington: Seattle, WA, USA)
- Fitter AH, Hay RKM (2002) 'Environmental physiology of plants.' (Academic Press: San Diego, CA, USA)
- Flowers TJ, Galal HK, Bromham L (2010) Evolution of halophytes: multiple origins of salt tolerance in land plants. *Functional Plant Biology* **37**, 604–612. doi:10.1071/FP09269
- Foster PR, Reseigh J, Myers RJ (2010) 'An introduction to the nutritional composition of Australian native grasses: forage and seed.' (Rural Solutions and Primary Industries: Adelaide, S. Aust.)
- Fulkerson WJ, Slack K, Havilah E (1999) The effect of defoliation interval and height on growth and herbage quality of kikuyu (*Pennisetum clandestinum*). *Tropical Grasslands* **33**, 138–145.
- Gammage B (2011) 'The biggest estate on Earth.' (Allen and Unwin: Crows Nest, NSW)
- García SC, Islam MR, Clark CEF, Martin PM (2014) Kikuyu-based pasture for dairy production: a review. *Crop & Pasture Science* **65**, 787–797. doi:10.1071/CP13414
- Ghaly FM (2002) Role of natural vegetation in improving salt affected soil in Northern Egypt. *Soil & Tillage Research* **64**, 173–178. doi:10.1016/S0167-1987(01)00240-9
- Hanna WW, Chaparro CJ, Mathews BW, Burns JC, Sollenberger LE, Carpenter JR (2004) Perennial *Pennisetums*. In 'Warm season (C₄) grasses'. (Eds LE Moser, BL Burson, LE Sollenberger) pp. 520–526. (Agronomy Society of America, Inc.: Madison, WI, USA)
- Hanselka CW, Hussey MA, Ibara F (2004) Buffelgrass. In 'Warm-season (C₄) grasses'. (Eds LE Moser, BL Burson, LE Sollenberger) pp. 477–502. (Agronomy Society of America, Inc.: Madison, WI, USA)

- Helalia AM, El-Amir S, Abou-Zeid ST, Zaghoul KF (1992) Bio-reclamation of saline-sodic soil by amshot grass in North Egypt. *Elsevier. Soil & Tillage Research* **22**, 109–115. doi:10.1016/0167-1987(92)90025-7
- Helfgott SF (1994) *Pennisetum clandestinum* Hochst. ex Chiov. In 'Weed management for developing countries'. (Eds R Labrada, JC Caseley, C Parker) pp. 72–73. (FAO: Rome)
- Heuzé V, Tran G, Sauvant D (2015a) Dallis grass (*Paspalum dilatatum*). Cereal and grass fodder. Feedipedia. INRA, CIRAD, AFZ and FAO. Available at: www.Feedipedia.org/node/404 (accessed July 2016)
- Heuzé V, Tran G, Delagarde R, Lebas F (2015b) Bermuda grass (*Cynodon dactylon*). Cereal and grass fodder. Feedipedia. INRA, CIRAD, AFZ and FAO. Available at: www.Feedipedia.org/node/471 (accessed July 2016)
- Heuzé V, Tran G, Sauvant D (2015c) Red oat grass (*Themeda triandra*). Cereal and grass fodder. Feedipedia. INRA, CIRAD, AFZ and FAO. Available at: www.Feedipedia.org/node/367 (accessed July 2016)
- Heuzé V, Tran G, Baumont R, Lebas F (2016) Buffel Grass (*Cenchrus clandestinus*). Cereal and grass fodder. Feedipedia. INRA, CIRAD, AFZ and FAO. Available at: www.Feedipedia.org/node/482 (accessed July 2016)
- Holton TA, Skabo SJ, Lowe KF, Sinclair K (2007) Genetic fingerprinting of natural kikuyu population in Australia. *Tropical Grasslands* **41**, 236–237.
- Humphreys LR (1967) Buffel grass (*Cenchrus ciliaris*) in Australia. *Tropical Grasses* **1**, 123–134.
- Jauhar pp. (1981) 'Cytogenetics and breeding of pearl millet and related species'. In 'Progress and topics in cytogenetics'. (Alan R. Liss: New York)
- Khumalo TP (2015) Genetic identification of kikuyu grass (*Pennisetum clandestinum*) cultivars by RAPD and ISSR techniques. MSc Thesis, The University of Kwazulu-Natal, South Africa.
- Lipshitz N, Waisel Y (1974) Existence of salt glands in various genera of the Gramineae. *New Phytologist* **73**, 507–513. doi:10.1111/j.1469-8137.1974.tb02129.x
- Luckett D, Kaiser A, Virgona J (1996) Innovative breeding of high-digestibility kikuyu cultivars to increase milk production. Final report, DAN 063. Dairy Research and Development Corporation, Melbourne.
- Marais J (2001) Factors affecting the nutritive value of kikuyu grass (*Pennisetum Clandestinum*)—a review. *Tropical Grasslands* **35**, 65–84.
- Marcum KB (1999) Salinity tolerance mechanisms of grasses in the subfamily Chloridoideae. *Crop Science* **39**, 1153–1165. doi:10.2135/cropsci1999.0011183X003900040034x
- Masters DG, Benes SE, Norman HC (2007) Biosaline agriculture for forage and liversock production. *Agriculture, Ecosystems & Environment* **119**, 234–248. doi:10.1016/j.agee.2006.08.003
- Mears PT (1970) Kikuyu—(*Pennisetum clandestinum*) as a pasture grass—a review. *Tropical Grasses* **4**, 139–152.
- Meredith D (1955) 'The grasses pastures of South Africa.' (Central News Agency: Capetown, South Africa)
- Morgan JM, Condon AG (1986) Water use, grain yield and osmoregulation in wheat. *Australian Journal of Plant Physiology* **13**, 523–532. doi:10.1071/PP9860523
- Morris B (2007) Breeding kikuyu for the future. Research report. *Australian Turf Grass Management*, Vol. 9.4, pp. 58–61.
- Morris B (2009) Variation and breeding of kikuyu grass (*Pennisetum clandestinum*). PhD Thesis, Plant Breeding Institute, The University of Sydney, NSW, Australia.
- Morrone O, Aagesen L, Scatagliani MA, Salariato DL, Denham SS, Chemisguay MA, Sede SM, Giussani LM, Kellogg EA, Zuloaga FO (2012) Phylogeny of the Paniceae (Poaceae: Panicoideae) integrating plastid DNA sequences and morphology into a new classification. *Cladistics* **28**, 333–356.
- Munns R (2005) Tansley review. Genes and salt tolerance: bringing them together. *New Phytologist* **167**, 645–663. doi:10.1111/j.1469-8137.2005.01487.x
- Muscolo A, Sidari M, Panuccio MR (2003) Tolerance of kikuyu grass to long term salt stress is associated with induction of antioxidant defences. *Plant Growth Regulation* **41**, 57–62. doi:10.1023/A:1027378417559
- Muscolo A, Panuccio MR, Eshel A (2013) Ecophysiology of *Pennisetum clandestinum*: a valuable salt tolerant grass. *Environmental and Experimental Botany* **92**, 55–63. doi:10.1016/j.environbot.2012.07.009
- Narayan K (1955) Cytogenetic studies of apomixis in *Pennisetum (Pennisetum Clandestinum)* Hochst. *Proceedings of the Indian Academy of Sciences. Section B, Biological Sciences* **45**, 196–208.
- National Land and Water Resources Audit (2000) 'Australian dryland salinity assessment Audit 1. Commonwealth of Australia. (The National Land and Water Resources Audit, Land & Water Australia: Canberra, ACT)
- National Land and Water Resources Audit (2001) 'Australian agriculture assessment. Vol 1.' (National Land and Water Resources Audit, Land & Water Australia: Canberra, ACT)
- Parker DL (1941) Strain variation and seed production in kikuyu grass (*Pennisetum clandestinum* Hochst). *Journal of Agriculture of South Australia* **45**, 55–59.
- Pessaraki M, Szabolcs I (1999) Soil salinity and sodicity as particular plant/crop stress factors. In 'Handbook of plant and crop stress'. (Ed. M Pessaraki) pp. 3–21. (Marcel Dekker, Inc.: New York)
- Radhakrishnan M, Waisel Y, Sternberg M (2006) Kikuyu grass: a valuable salt-tolerant fodder grass. *Communications in Soil Science and Plant Analysis* **37**, 1269–1279. doi:10.1080/00103620600623590
- Reeves M, Fulkerson WJ, Kellaway RC (1996) Forage quality of kikuyu (*Pennisetum clandestinum*): the effect of time of defoliation and nitrogen fertiliser application and in comparison with perennial ryegrass (*Lolium perenne*). *Australian Journal of Agricultural Research* **47**, 1349–1359. doi:10.1071/AR9961349
- Robinson PH, Grattan SR, Getachew G, Greive CM, Poss JA, Suarrr DL, Benes SE (2004) Biomass accumulation and potential nutritive value of some forages irrigated with saline-sodic drainage water. *Animal Feed Science and Technology* **111**, 175–189. doi:10.1016/S0377-8401(03)00213-X
- Rogers ME, Craig DA, Munns RE, Colmer TD, Nichols PGH, Malcolm CV, Barrett-Lennard EG, Brown AJ, Semple WS, Evans PM, Cowley K, Hughes SJ, Snowball R, Bennett SJ, Sweeney GC, Dear BS, Ewing MA (2005) The potential for developing fodder plant for the salt-affected areas of southern and eastern Australia: an overview. *Australian Journal of Experimental Agriculture* **45**, 301–329. doi:10.1071/EA04020
- Rosenzweig C, Iglesias A, Yang XB, Epstein PR, Chivian E (2001) 'Climate change and extreme weather events—implications for food production, plant disease, and pests.' pp. 24. (NASA Publications). Available at: http://digitalcommons.unl.edu/nasapub/24 (accessed October 2016)
- Ross BA (1999) *Pennisetum clandestinum* in Australia. In 'Forage seed production. Volume 2: Tropical and subtropical species'. (Eds DS Loch, JE Ferguson) pp. 387–394. (CABI Publishing: Wallingford, UK)
- Roy S, Chakraborty U (2014) Salt tolerance mechanisms in Salt Tolerant Grasses (STGs) and their prospects in cereal crop improvement. *Botanical Studies* **55**, 31. doi:10.1186/1999-3110-55-31
- Rumman GA (2011) Ecophysiology of salt tolerance in three halophytic turfgrasses. PhD Thesis, School of Plant Biology, University of Western Australia, Crawley, W. Aust.
- Russell FS (1976) Comparative salt tolerance of some tropical and temperate legumes and tropical grasses. *Australian Journal of Experimental Agriculture and Animal Husbandry* **16**, 103–109. doi:10.1071/EA9760103
- Russell JS, Webb HR (1976) Climatic ranges of grasses and legumes used in pasture: Results of the survey conducted at the 11th International

- Grassland Congress. *Journal of the Australian Institute of Agricultural Science* **42**, 156–166.
- Sanderman J, Fillery IRP, Jongepier R, Massalsky A, Roper MM, Macdonald LM, Maddern T, Murphy DV, Wilson BR, Baldock JA (2013) Carbon sequestration under subtropical perennial pasture 1: Overall trends. *Soil Research* **51**, 760–770. doi:[10.1071/SR13111](https://doi.org/10.1071/SR13111)
- Skerman PJ, Riveros F (1990) 'Tropical grasses.' FAO Plant Production and Protection Series. (FAO: Rome)
- Sokal RR, Michener CD (1958) A statistical method for evaluating systematic relationships. *The University of Kansas Science Bulletin* **38**, 1409–1438.
- Stapf O (1921) Kikuyu grass (*Pennisetum clandestinum* Chiov). In 'Bulletin of Miscellaneous Information'. Vol. 2, pp. 85–93. (Royal Botanic Gardens: Kew, UK)
- Turner NC (1999) Drought stress and adaptive responses. In 'Plants in action'. (Eds BJ Atwell, PE Kriedemann, CGN Turnbull) pp. 482–484. (Macmillan Publishers: Melbourne)
- Valliyodan B, Nguyen HG (2006) 'Understanding regulatory networks and engineering for enhanced drought tolerance in plants. *Current Opinion in Plant Biology* **9**, 189–195. doi:[10.1016/j.pbi.2006.01.019](https://doi.org/10.1016/j.pbi.2006.01.019)
- Wheeler DJB, Jacobs SWL, Wally RDB (2002) 'Grasses of New South Wales.' pp. 327–328. (The University of New England: Armidale, NSW)
- Whittet JN (1921) A promising introduction. *Agricultural Gazette of New South Wales* **32**, 313–323.
- Wilen CA, Holt JS (1996) Physiological mechanisms for the rapid growth of *Pennisetum clandestinum* in Mediterranean climates. *Weed Research* **36**, 213–225. doi:[10.1111/j.1365-3180.1996.tb01651.x](https://doi.org/10.1111/j.1365-3180.1996.tb01651.x)
- Williams JGK, Kubelik AR, Livak KJ, Tingey SJ (1990) DNA polymorphic amplified by arbitrary primers are useful as genetic markers. *Nucleic Acids Research* **18**, 6531–6535. doi:[10.1093/nar/18.22.6531](https://doi.org/10.1093/nar/18.22.6531)
- Wilson GPM (1968) New kikuyu variety performs well in Grafton. *Agricultural Gazette of New South Wales* **79**, 51.
- Wolfe E (2009) 'Country pasture/forage resource profile Australia.' (FAO: Rome)
- Youngner VB (1961) Observation on the ecology and morphology of *Pennisetum clandestinum*. *Phyton* **16**, 77–84.