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Strawberry clover (*Trifolium fragiferum*): current status and future role in Australian agriculture

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ABSTRACT

Strawberry clover (*Trifolium fragiferum* L.) is periodically raised as an alternative perennial pasture legume for temperate regions of Australia. Its tolerance of waterlogging is widely known, yet its ability to persist through periods of soil moisture deficit is often understated. Other desirable characteristics include its stoloniferous growth habit and tolerance of mildly saline conditions. Only four strawberry clover cultivars have been registered in Australia, and the most popular, cv. Palestine, is a direct introduction, released in 1938 and first certified in 1951. Furthermore, strawberry clover's distribution has largely been confined to niche environments, particularly waterlogged and saline areas. This paper reviews the taxonomy and breeding system, morphology, distribution and ecology, and subsequent transfer of strawberry clover to Australia. It reviews and maps the suitability of strawberry clover for perennial pasture systems in the medium–high rainfall and irrigated temperate zones of Australia, with reference to future climates. The paper also highlights the breeding focus, commercialisation and marketing required to supersede cv. Palestine and lists the germplasm available in the Australian Pastures Genebank, with origins. We conclude that, although strawberry clover is unlikely to become a dominant perennial pasture legume species in Australia, it could be used in a wider range of environments than just those affected by salinity and/or waterlogging stress.

Keywords: cultivars, germplasm, legumes, pastures, perennial, review, stress tolerance, suitability, waterlogging.

Introduction

The benefits of including legumes in mixed pasture swards are well understood. Most notably, legumes increase groundcover, improve nutritional quality of grazed forage, and provide nitrogen for companion pasture species and future crops grown in rotation (Howieson *et al.* 2008; Nichols *et al.* 2012). Relative to annual plants, perennial legumes can reduce the detrimental impacts of dryland salinity from rising water tables by utilising soil water from greater depths and for longer periods (Dunin *et al.* 1999; Fillery and Poulter 2006; Ward and Micin 2006). Despite these advantages, only three temperate perennial legumes, lucerne (*Medicago sativa* L.), white clover (*Trifolium repens* L.) and, to a lesser extent, red clover (*T. pratense* L.), are widely sown in Australia (Dear *et al.* 2003). Oram (1993) outlined the reasons for expanding the number and area of alternative legumes as: (1) the need to fill diverse ecological niches within paddocks; (2) better buffering against pests and diseases; and (3) improving sustainable soil management. In addition, recent research has shown that alternative legumes may have a role in reducing methane emissions from livestock (Badgery *et al.* 2023) and reducing incidence of metabolic disorders in livestock associated with issues such as bloat (Marshall *et al.* 1979) and mineral imbalance (Refshauge *et al.* 2022).

Identification and adoption of perennial legume species that will prosper in climates and soil types where the traditional species fail to persist remains an opportunity for pastoral systems. This will be particularly important for adaptation of pastoral systems to the drier climate and increased frequency of extreme climatic events predicted for much of southern Australia, which are likely to reduce annual pasture production (Harrison *et al.* 2016; Harrison *et al.* 2017). Dear *et al.* (2003) and Li *et al.* (2008) suggested strawberry clover (*T. fragiferum* L.) as one of only a few alternative perennial legumes that offer greatest immediate potential for southern Australia, along with sainfoin (*Onobrychis viciifolia* Scop.), sulla (*Hedysarum coronarium* L.) and several *Lotus* species; more recently, Real *et al.* (2014) also suggested tedera (*Bituminaria bituminosa* C.H. Stirton var. *albomarginata*) as an alternative. As observed by Morley (1963):

> Strawberry clover has long been identified as a candidate perennial pasture legume, which responds to summer rains, and grows well, and produces nitrogen in other seasons in regions rather too dry for white clover.

Strawberry clover is an interesting species with unfulfilled potential, remaining a niche perennial legume species in pasture systems worldwide. Likely reasons for limited adoption is that it lacks the dry matter (DM) production of white clover (Kemp *et al.* 2002; Gerard *et al.* 2022), the persistence of lucerne in dry environments (Li *et al.* 2008), or the vigour of red clover (Dear *et al.* 2003). However, strawberry clover has waterlogging and salinity tolerance superior to any of these species (Nichols *et al.* 2008). It also can persist through dry summers and spread rapidly via above-ground stolons when soil moisture returns to non-limiting levels. It is perceived to be sensitive to soil acidity (Pires *et al.* 1992; Wheeler and Dodd 1995; McVittie *et al.* 2012; Moir *et al.* 2016; Hayes *et al.* 2023), an issue examined in some detail in this review owing to the extent of soil acidity across much of southern Australia.

Only two cultivars of strawberry clover (Palestine and O'Connors) are currently grown for certified seed in Australia, with cv. Palestine comprising >94% of seed production over the past 5 years (Australian Seeds Authority 2021*a*, 2021*b*). Two New Zealand cultivars (Grasslands Onward and Grasslands Upward) were developed in the 1980s (Rumball *et al.* 1991*a*, 1991*b*), but have had little impact in Australia. Several authors, including Craig (1994), McDonald *et al.* (2005), Rogers *et al.* (2005), Li *et al.* (2008), and Nichols *et al.* (2008), have suggested opportunities for developing improved strawberry clover cultivars for Australian conditions. This review examines the use of strawberry clover in pastures, considers its strengths and weaknesses, and presents a case for further research and breeding efforts to enable greater use in future farming systems.

Taxonomy and morphological description

Strawberry clover was included as the species *Trifolium fragiferum* by Linnaeus (1753) in his botanical work 'Species Plantarum'. In their taxonomic revision of the genus *Trifolium*, Zohary and Heller (1984) categorised strawberry clover as follows:

Family:	*Fabaceae*
Tribe:	*Trifolieae*
Section:	*Vesicaria* (*T. fragiferum* is the lectotype for this Section)
Genus:	*Trifolium*
Species:	*fragiferum*

Ellison *et al.* (2006), in a phylogenetic study of the *Trifolium* genus, suggested a new classification, with *T. fragiferum* placed in section *Vesicastrum* within subgenus *Trifolium* of the genus *Trifolium*.

An extensive botanical description of strawberry clover can be found in Zohary and Heller (1984). Strawberry clover is generally prostrate in growth (although genotypes vary), originating as a tap-rooted seedling (Frame 2005), before it develops secondary root branching and spreads vegetatively via creeping stems (stolons) that can root at the nodes (Hollowell 1939; Tiver 1954; Forde *et al.* 1981) (Fig. 1*a*–*d*). It has some similarities to white clover, but can be distinguished from that species in the field by having leaflets more oval in shape and distinctly different flower heads that are more rounded and pink in colour, and a composite fruit containing dried petals, resembling the structure of a strawberry (Hollowell 1939; Tiver 1954) (Fig. 1*b*, *e*). Leaf markings in strawberry clover cultivars tend to be less prominent than those of white clover, typically ranging from no marking (Fig. 1*b*) to a broad, pale green chevron. Seeds are light brown (Frame 2005) (Fig. 1*f*), with 660 000–770 000 seeds/kg (Tiver 1954; Forde *et al.* 1981; Frame 2005). Zohary and Heller (1984) further describe five botanical varieties of *T. fragiferum*: var. *fragiferum*, var. *majus*, var. *modestum*, var. *pulchellum* and var. *orthodon*. These varieties differ slightly in morphology and natural distribution. Variety *fragiferum* has more botanical specimens and a broader distribution, with the other varieties being much rarer (Zohary and Heller 1984). On this basis, it appears most likely that cv. Palestine belongs to var. *fragiferum*. It is not known to which variety other germplasm in Australian collections belong.

The breeding system of strawberry clover has been debated by several authors. Early work on strawberry clover claimed that the species was self-fertile (Williams 1931, in Davies 1971), although research by Morley (1963) and Wright (1964) found that it was outcrossing and predominantly self-sterile. Davies (1971) points out that 11 of 63 clones in the crossing data from Wright (1964) set an average of 46% seed autogamously, suggesting a breeding system with variable self-compatibility. Davies and Young (1966) found strawberry clover largely self-sterile, following examination of accessions collected from Europe and in material derived from the accessions, but they also found a small percentage of plants that were self-fertile. By contrast, some populations were largely self-fertile in northern Europe with ability to be

Fig. 1. *Trifolium fragiferum* L.: (*a*) full plant; (*b*) leaf; (*c*) primary taproot with secondary roots including nodules; (*d*) stolon with rooting at the nodes and daughter plantlets; (e) flower head being cross-pollinated by honeybee; (*f*) seed. Photo credits: S. Manik (*a*, *c*), J. Talbot (*b*, *d*, *f*), A. Hurst (e) (Tasmanian Institute of Agriculture).

maintained under selfing conditions without loss of vigour or self-fertility (Davies 1971). One hypothesis for this might be a lack of suitable pollinators in more northerly climates. Regardless, strawberry clover flowers are cross-pollinated by honey bees (Frame 2005) (Fig. 1*e*).

Origin and distribution

Native distribution and habitat

On the basis of reported botanical specimens, Zohary and Heller (1984) claim strawberry clover to be native to all European countries (including the British Isles), all other Mediterranean countries, and West and Central Asia (including western Siberia, the Caucasus and Turkestan regions, Iraq, Iran, Afghanistan and Pakistan), and it has also been recorded in Ethiopia. This distribution is supported by seed collection site information, referred to as 'passport data', consisting of latitude, longitude, altitude, temperature and rainfall parameters, and soil pH and texture for 480 geo-referenced wild populations, referred to as 'accessions'. These are held in genebanks worldwide, with a total of 1095 collected accessions (Genesys 2022; Fig. 2).

Strawberry clover is relatively tolerant of flooding and of moderately saline soils (up to 20 mM NaCl), being commonly found in low-lying swampy, or occasionally saline, environments (Townsend 1985). It has been collected across a wide range of latitudes (15.4–55.6°N) and elevations (−20 to 2278 m a.m.s.l.). Cv. Palestine was collected as an ecotype in Israel close to the Dead Sea (Barnard 1972*a*). A comparison of the passport data for cv. Palestine with those for accessions collected from extremes in its native distribution for temperature, latitude, elevation and rainfall is shown in Table 1. Accessions have been collected in environments with mean temperatures in the warmest quarter >30°C and maximum temperatures in the warmest month of 40°C; at the other extreme, accessions have been collected in environments with average minimum temperatures in the coldest month as low as −25°C. Strawberry clover has also been collected in environments with average annual rainfall from 98 to 1718 mm. However, the lower rainfall limit *per se* may be misleading, because strawberry clover is often found in the most favoured niches within localities such as irrigation ditches or watercourses. Genesys data

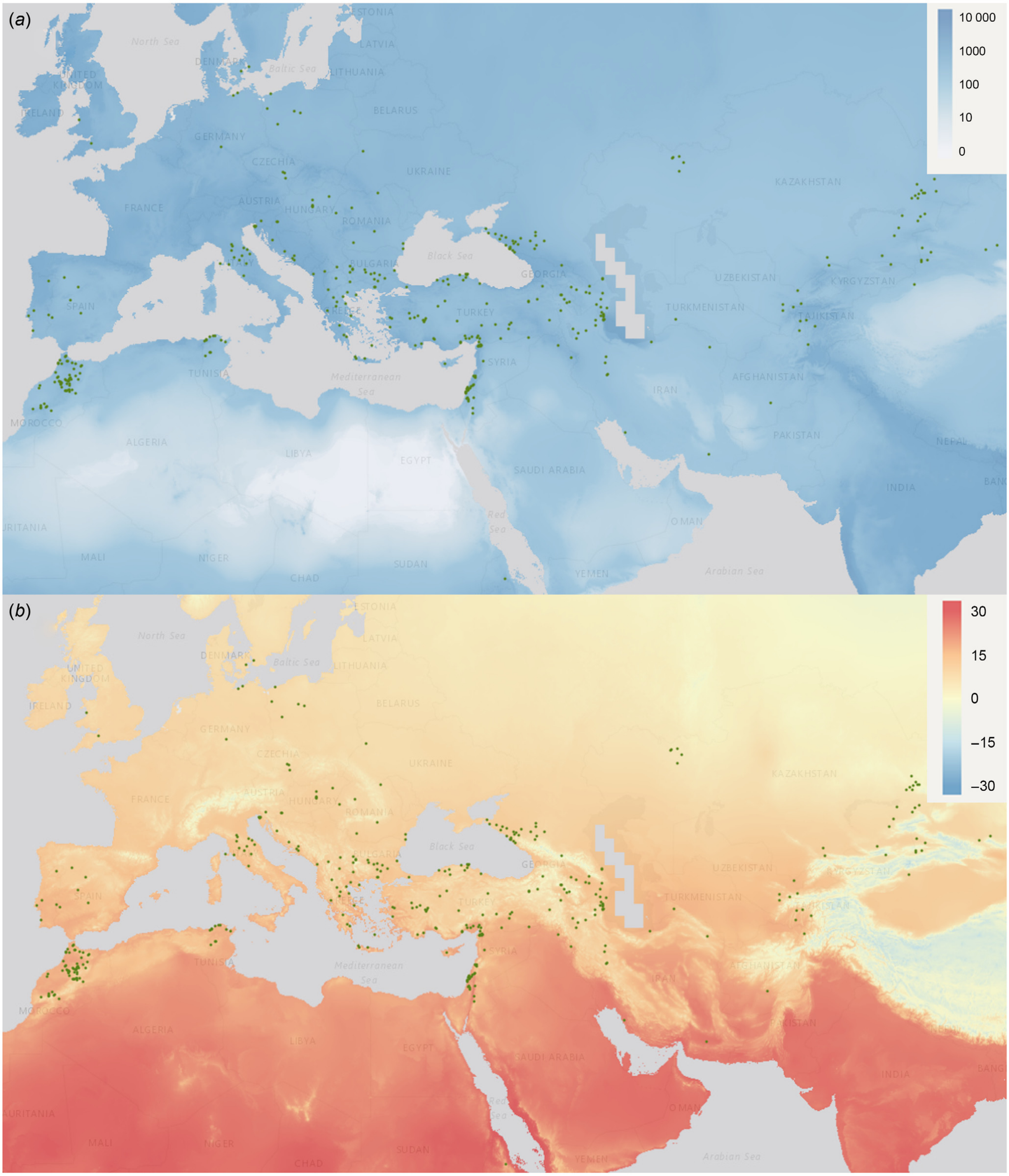

Fig. 2. Distribution of strawberry clover accessions collected in Europe, Africa and Asia, overlayed by (*a*) rainfall (mm) and (*b*) mean daily temperature (°C), available in worldwide genebanks. Information from www.Genesys-pgr.org (an online platform for information about plant genetic resources conserved in genebanks worldwide).

(Genesys 2022) were used, in combination with satellite maps in Google Earth, to identify accessions growing in low-rainfall environments with minimal supplementary water. The presence of wild strawberry clover populations in very hot

Table 1. Strawberry clover (*T. fragiferum*) accessions representing extremes in diversity based on collection origin and its climate, compared with the climate origin of cv. Palestine.

Selection criterion for accession	OS	ACCENUMB	ORIGCTY	INSTCODE	AAR	LAT	LONG	ELEV	MinT	MaxT	MeanT WQtr	Collection Notes
cv. Palestine (commercial cultivar)		APG 383	ISR	AUS167	473–567	32.00	35.00	50	5.4	31	25	From an ecotype in Israel near the Dead Sea
1. Max. temp. of warmest month is at least 40°C	9	APG 42327	AZE	AUS167	**337**	41.68	48.75	−10	−1.6	**40**	25.2	Coast of the Caspian Sea on non-wetting beach sand
	2	APG 14346	SYR	AUS167	440	37.05	41.25	450	3	**40.2**	**30.6**	El Qamishliye public park
	2, 9	PI 250789	AFG	USA022	**173**	31.62	65.72		−0.6	**40.9**	**30.5**	Kandahar, 'dry areas near road'
	2	PI 254916	IRQ	USA022	697	35.42	45.57		1	**40.1**	**31**	Collected as an annual
2. Mean temp. of warmest quarter >29°C	9	PI 381047	IRN	USA022	**98**	27.12	59.42		10.4	40	**33**	Roadside ditch
3. Min. temp. of coldest month is at least 10°C (mild temp, no frost)	1, 9	IG 66920	IRN	LBN002	**207**	29.00	51.05	15	**10**	37.6	32.5	
4. Min. temp. of coldest month −25°C (coldest winter)		APG 38814	KAZ	AUS167	338	48.70	82.25	523	**−25.8**	27.1	18.5	Grassland riverbed site near Ayagoz
5. Max. temp. of warmest month is at most 19°C (mild maximum)		W6 26356	GEO	USA022	999	42.65	44.63		−13.2	**17.6**	10.3	
6. Max. northern latitude		ABY-Ah 2175	SWE	GBR016	621	**55.67**	13.08		−2.5	20.4	16.1	
7. Max. southern latitude, Max Elevation		APG 81003	ERI	AUS167	470	**15.42**	38.87	**2278**	6.3	26.2	18.6	
8. Min. elevation		APG 41966	AZE	AUS167	350	39.40	49.17	**−20**	0.5	31.9	25.2	Irrigation channels
9. Low AAR with minimal supplementary water <350		APG 14342	JOR	AUS167	**202**	31.18	35.62	650	5.7	33.1	25.5	Very dry environment, edge of irrigation channel
		PI 499683	CHN	USA022	**182**	44.10	88.51		−19.7	31.2	23	Very dry environment but on creek line
		PI 655921	TKM	USA022	**225**	38.49	56.12		−2.8	36	27.9	Elevated above river
		APG 62166	MAR	AUS167	**277**	32.70	−4.77	1480	0.1	34.2	23.5	Dry environment but with possible irrigated channel
		APG 38691	KAZ	AUS167	**296**	46.32	81.22	328	−18	31.7	22.4	Low swampy, dry saline flat
		IG 66934	IRN	LBN002	**332**	37.73	45.75	1272	−5.1	32.1	23.2	Dry environment, no obvious watercourse or irrigation
		APG 14343	JOR	AUS167	**350**	30.70	35.63	1400	−0.4	27.4	19.7	Grassland meadow
10. High AAR		W6 18670	ALB	USA022	**1718**	42.01	19.51		2.2	30.2	24	

Data from Genesys, https://www.genesys-pgr.org/.
OS, other bio-climatic selection variable(s) identified for this accession corresponding to the number in selection criteria column; ACCENUMB, Australian Pastures Genebank accession number; ORIGCTY, country of origin; INSTCODE, Genebank Institute Code; AAR, average annual rainfall (mm); LAT, latitude; LONG, longitude; ELEV, elevation (m a.m.s.l.); MinT, average minimum temperature of coldest month (°C); MaxT, average maximum temperature of warmest month (°C); MeanT WQtr, mean temperature of warmest quarter (°C). Values in bold are those for selected variable(s).

and dry environments suggests potential to improve the heat and drought tolerance of cultivars.

Subsequent transfer to Australia

Outside its native range, strawberry clover has spread to Australia, New Zealand and western USA (Townsend 1985; Frame 2005). It is unclear how and when it first came to Australia. According to Whittet (1964*a*), the introduction of strawberry clover to Australia was by design for the purposes of pasture improvement. However, it is likely that the first strawberry clovers were introduced accidentally into Australia as seed contaminants of other agricultural seeds, fodder, wool fleeces or packing containers imported in the late 18th and 19th centuries, in a manner similar to other exotic pasture legumes (Gladstones 1966; Nichols *et al.* 2012). Naturalised strawberry clover populations are known to have become established in the south-east of South Australia and in the Hunter region of New South Wales (NSW) prior to the 1890s, when they were first commercialised, later becoming known as cvv. O'Connors and Shearmans, respectively) (Barnard 1972*a*, 1972*b*). However, cv. Palestine, the most widely used strawberry clover in Australia, was a deliberate introduction in 1929 from Zimbabwe (formerly Rhodesia), having been originally collected as an ecotype from Israel (Barnard 1972*c*).

Breeding and cultivar development

Existing cultivars: strains, origins and utilisation

Early development of strawberry clover in Australia was founded largely on locally adapted strains. More than 20 strains from Australia, New Zealand and the USA were characterised by Tiver (1954). O'Connors was the name given to a strain that developed over more than 30 years in the Penola district in south-eastern South Australia and was known for its value on poorly drained soils (Tiver 1954). It is a more prostrate strain than cv. Palestine, with smaller leaves and finer runners, making it more tolerant of close grazing, although less productive, particularly in winter (Tiver 1954).

Similar to O'Connors, Shearmans was a locally adapted biotype that was directly multiplied for sale (Donald 1970) but was considered a distinct variety of strawberry clover and named by Breakwell (1923). It was first recognised in 1897 and subsequently cultivated by a dairy producer on marshy saline soils near Newcastle, NSW (Breakwell 1923). Early observations under such conditions suggested that Shearmans was faster spreading and grew more herbage than the known strawberry clover strain at the time, but produced little seed (Breakwell 1923); the last of these observations was later contradicted in South Australia according to Tiver (1954). Other early Australian strains included Hamilton, Parklands and Swan Hill, which were characterised as having medium leaf size, being finer and more prostrate and generally of poor winter production (Tiver 1954). Later, Prinsep Park (sometimes spelt Princep Park; Nichols *et al.* 2012) was selected out of Palestine in the Bunbury region of Western Australia (WA) with comparable persistence and yield (McDonald 2006).

Cultivar Palestine was the first certified in Australia in 1951 by the South Australian Department of Agriculture (Donald and Trumble 1940; Barnard 1972*a*; Australian Pastures Genebank 2022). The ecotype from which it is derived was found in Israel near the Dead Sea (Barnard 1972*a*; Nichols *et al.* 2012) and introduced to Australia in 1929 by HC Trumble; cv. Palestine was commercially available from 1938 (Tiver 1954). It was described by Tiver (1954) as a vigorous and erect strain with coarse runners and large leaflets, providing good winter production and flowering earlier than cv. O'Connors. Donald (1970) suggested that it had proven to be 'outstanding value on 400 000 ha of winter flooded rendzina soils in south-east South Australia' but had not been extensively adopted elsewhere in Australia. It remains the most widely cultivated variety (Australian Seeds Authority 2021*a*, 2021*b*). Phenotypic variation within and among Australian populations of strawberry clover cv. Palestine has been studied, using seed collected from five different environments in WA (McDonald *et al.* 2005). The results showed that, although considerable within-population variation exists, the five populations exhibit significantly different traits including leaf markers, growth habit, flowering time, plant width and height, seed production and seed size. The authors concluded that large variation existed within strawberry clover cv. Palestine in Australia, with the potential to express different phenotypes as it evolves to adapt to different environments.

Salina is one of the two main cultivars developed in the USA by selection within cv. Palestine (Townsend 1985; Frame 2005). It was developed for Californian conditions (Forde *et al.* 1981) and released in 1962 by the Californian Agricultural Experiment Station (Oregon State University 2022). Cv. Fresa was developed by New Mexico State University and was released in 1982 for turf purposes from material collected in Turkey (Frame 2005; Oregon State University 2022). It was actively selected for its low dense habit and found to be less than half as productive as cvv. Palestine, O'Connors and Salina (Baltensperger *et al.* 1982; Baltensperger and Gaussoin 1984).

Grasslands Onward was developed in New Zealand by W Rumball of AgResearch at Palmerston North in the 1980s (IP Australia 2022), released in New Zealand in 1991 (Rumball *et al.* 1991*a*), and granted Plant Breeder's Rights (PBR) registration in Australia in 1997 (IP Australia 2022). The parent material originates from a range of germplasm including naturalised New Zealand germplasm, wild accessions collected in Europe, and commercial seed lines including O'Connors and Palestine (Rumball *et al.* 1991*a*). Cv. Grasslands

Onward is most similar to O'Connors, being small-leaved, compact and prostrate, yet is more productive and best suited to sheep grazing (Rumball *et al.* 1991*a*). Grasslands Upward was developed in conjunction with Grasslands Onward from the same broad range of germplasm, but plants were selected for a more erect, open type suitable for dairy pastures (Rumball *et al.* 1991*a*, 1991*b*). The cultivar is thus more similar to cv. Palestine (Rumball *et al.* 1991*b*). Field evaluations in New Zealand showed Grasslands Onward and Grasslands Upward to have performance superior to cvv. O'Connors and Palestine, respectively (Rumball *et al.* 1991*a*, 1991*b*). However, they have had limited commercial success in Australia, with PBR registration of Grasslands Onward being terminated in 2007 (IP Australia 2022). In 2005, the turf-type germplasm 'GAO153' was released by AgResearch Grasslands in New Zealand for the purpose of low maintenance, dense groundcover, similar to cv. Fresa (Rumball and Claydon 2005).

Commercial seed production

Cultivars O'Connors and Palestine, both of which are maintained by the South Australian Research and Development Institute (SARDI), are now the only eligible varieties for certification in Australia (Australian Seeds Authority 2021*c*). In the 1952–53 season, certified seed of O'Connors reached 20 t, whereas that of Palestine was 50 t (Gorman 1953). By comparison, in the 5 years to 2021, mean certified seed production (under OECD, AOSCA and Australian Certification Schemes) of O'Connors was 4 t and cv. Palestine 48 t (Australian Seeds Authority 2021*b*). According to Lucas (2020), there was no seed production of proprietary strawberry clover cultivars between 2014 and 2018 in Australia.

Agronomy

Productivity

Strawberry clover is commonly considered less productive than white and red clovers. This appears to be an issue of lower production potential rather than a density-dependent relationship, from observations in both spaced-plant and plot experiments (Kemp *et al.* 2002; Gerard *et al.* 2022). On the Central Tablelands of NSW, Kemp *et al.* (2002) observed inconsistent growth of strawberry clover, producing comparable aboveground DM yields to white clover only under favourable conditions, and in drier years producing only 20% of the aboveground DM of subterranean clover. Li *et al.* (2008) found that strawberry clover was more productive and persistent than white clover at two sites in WA and one site in NSW, but was less productive than lucerne.

We can only speculate as to the apparent disparity of results reported by Kemp *et al.* (2002) and Li *et al.* (2008). In the former study, strawberry clover performance was inconsistent and inferior to white clover, compared with the latter, where strawberry clover performance surpassed white clover and approached that of lucerne. Although site descriptions for both studies are brief, it is probable that the more fertile topsoil was substantially deeper at the sites reported by Li *et al.* (2008) but quite shallow at most of the sites reported by Kemp *et al.* (2002). It is also likely that summer temperatures were cooler at the NSW Central Tablelands sites (Kemp *et al.* 2002) than in the cropping environments reported by Li *et al.* (2008). Neither study reported prolonged periods of inundation at any site. White clover certainly favours cooler summer temperatures and is known to tolerate moderate soil acidity and infertility (Lane *et al.* 2000). Both lucerne (Norton *et al.* 2021) and strawberry clover (Hofmann *et al.* 2007) tolerate moisture stress better than white clover, helping to explain their superior persistence in the drier environments described by Li *et al.* (2008) compared with white clover.

Abiotic stress tolerance

Strawberry clover is generally purported to have better tolerance of abiotic stresses such as drought, salinity, waterlogging and extremes of temperature than many other temperate perennial forage legumes, particularly white clover (Tiver 1954; Dūmiņš *et al.* 2021). Salinity continues to be a major environmental problem in parts of Australia, as a consequence of the clearing of perennial vegetation causing rising water tables (National Land and Water Resources Audit 2001). This land may also be subject to waterlogging due to shallow water tables, or due to decreased infiltration of surface water or irrigation and poor drainage (Barrett-Lennard 2003). The productivity of conventional pastures in these saline and waterlogged areas is very low and has prompted efforts to develop improved fodder species for saline and waterlogged conditions (Rogers *et al.* 2005; Nichols *et al.* 2008). Less is known about the tolerance of strawberry clover to soil acidity.

Response to soil acidity and fertility

Strawberry clover is grown on soils in western USA that are wet, saline or alkaline, and it is generally advantaged by continuous grazing in mixed pastures (Van Keuren and Hoveland 1985). One of the primary limitations to the broader adaptation of strawberry clover in environments across southern Australian is its sensitivity to soil acidity and associated mineral toxicities. In hydroponic solution culture experiments, McVittie *et al.* (2012) compared species for seedling root and shoot reductions in response to elevated concentrations of aluminium (Al) and manganese (Mn), respectively, and reported that the response of strawberry clover cv. Palestine to both elements was similar to that of lucerne cv. SARDI 10. These results were broadly consistent with an earlier screening in hydroponic solution involving Al alone (Wheeler and Dodd 1995). Similarly, in a glasshouse experiment, Moir *et al.* (2016) demonstrated that strawberry clover had a response to lime and optimal pH similar to that of lucerne when grown in an acidic soil over a 10-month period. In a separate study, strawberry clover seedlings were shown to be highly sensitive to soil acidity and grew only when lime was applied (Pires *et al.* 1992). Together, these studies affirm the fundamental importance of ameliorating soil acidity for the successful establishment of strawberry clover seedlings.

Less is known about the relative tolerance to soil acidity of mature strawberry clover plants. Seedling response to soil acidity does not necessarily reflect mature plant performance in field environments. This is illustrated by the perennial grass phalaris (*Phalaris aquatica* L.); its seedlings are highly sensitive to Al toxicity, which prompted a breeding initiative to develop more tolerant cultivars (Culvenor *et al.* 1986, 2011). Yet, this species has been endemic across acidic soil environments of south-eastern Australia for many decades, and in the Millennial Drought, mature plants of phalaris persisted in acutely acidic soils better than some species regarded as more tolerant of acidity (Hayes *et al.* 2015). Key factors impacting strawberry clover performance in field environments include the severity of soil acidity, the extent to which low pH is associated with Al and Mn toxicities, and the depth of any acidic soil layer (i.e. the proportion of the root system impacted by low pH). Recruitment of seedlings is also likely to be reduced, owing to the seedling sensitivity of strawberry clover.

Soil acidity in a field environment can often be difficult to disentangle from other soil fertility properties because many acidic soils also have low fertility (Hayes *et al.* 2019). Low fertility in acidic soils can be caused directly or indirectly by soil acidity (Hayes *et al.* 2022), or can exist simply as an association due to factors such as the parent material from which the soil was derived. Most previous studies that have examined strawberry clover response to soil fertility issues other than pH have focused on phosphorus (P). In a glasshouse experiment using a P-deficient soil, Moir *et al.* (2016) observed a similar response to P fertiliser in strawberry clover and white clover. Both species achieved 'biologically optimum yields' at lower P-fertiliser rates than lucerne, which is known to have very high P requirements (Sandral *et al.* 2019). Caradus (1980) demonstrated in a pot experiment that the total root length of strawberry clover was only 30% of that of white clover, suggesting a relatively limited capacity of strawberry clover to explore the soil volume for nutrients compared with other legumes. Taken together, these studies suggest a vulnerability in strawberry clover on acidic soils, due not only to sensitivity to toxicities but also to low fertility conditions that are often associated with acidity. In practice, this suggests that strawberry clover is probably more suited to soil types with pH and fertility levels considered suitable for lucerne, or where lucerne might otherwise be suited but for a high risk of waterlogging. In a recent evaluation of perennial legume persistence in tableland environments of NSW, Hayes *et al.* (2022*a*) demonstrated that strawberry clover generally performed well at only a subset of sites, where lucerne also performed well.

A study conducted on the Central Tablelands of NSW showed the DM production of strawberry clover to be lower and more variable than either white or subterranean clover (Kemp *et al.* 2002). Although an extensive characterisation of soil type was not undertaken, those authors reported initial soil tests from the surface 10 cm as being generally acidic (pHCa ≤5.1), with low levels of Al (≤6% of cations) and variable P fertility (Bray P, 8–32 mg/L).

Waterlogging and salinity tolerance

In southern Australia, strawberry clover is often found in dryland areas that are poorly drained, sodic, waterlogged and/or saline, or where the soil pH is too alkaline for white clover (pH_{water} 8–9) (Craig 1994). Similarly, in irrigated regions, strawberry clover may be included in pastures if the irrigation water is too saline for white clover (Craig 1994).

Strawberry clover has been highlighted numerous times in multi-species evaluations for waterlogging and/or salinity tolerant forage legumes (Masters *et al.* 2001; Dear *et al.* 2003; Rogers *et al.* 2005; Masters *et al.* 2007; Dear and Ewing 2008; Striker and Colmer 2017). However, much of the research has also been conducted under controlled-climate conditions, making it challenging to extrapolate findings accurately to the field.

Strawberry clover's salinity tolerance was first documented ~80 years ago (Ahi and Powers 1938; Gauch and Magistad 1943), with the first Australian reports published by Tiver (1954) and Rogers and Bailey (1963). Most of this, and subsequent, research (Russell 1976; Mehanni and Repsys 1986; Craig 1994; Rogers *et al.* 1997*a*; Nichols *et al.* 2008; Rogers *et al.* 2009; Galloway *et al.* 2010) concluded that strawberry clover had moderate salinity tolerance, especially compared with other forage legumes. A conservative salinity threshold of 1–2 dS/m (~20 mM NaCl) has been identified as the maximum salinity level before strawberry clover herbage growth is depressed (Gauch and Magistad 1943; Rogers *et al.* 1997*b*). Strawberry clover's tolerance of saline conditions has been associated with the exclusion of Na^+ and Cl^- from the shoots and the maintenance of a reasonable internal K^+/Na^+ ratio (<2.0) (Rogers and West 1993; Munns 2005; Rogers *et al.* 2009; Dūmiņš *et al.* 2021).

Recent research by Dūmiņš *et al.* (2021), in a non-agricultural environment, confirmed strawberry clover's superior salinity tolerance compared with white clover and its adaptation to coastal saline sites. At 21 dS/m (~350 mM NaCl), strawberry clover's DM yield was depressed by 50% (Can *et al.* 2013). An extensive review of the salinity tolerance of a wide range of forages identified strawberry clover as one of 53 forage legumes with a potential role in 'salt-affected' Australian areas (Rogers *et al.* 2005). Based on this review, the salinity tolerances of 38 annual and perennial *Trifolium* species, including six strawberry clover genotypes, were evaluated under glasshouse conditions (Rogers *et al.* 2009). Again, strawberry clover proved to be one of the more salt-tolerant clover species, with significant intraspecific variation in the salinity tolerance of evaluated genotypes. At 160 mM NaCl (~9.5 dS/m), herbage growth of strawberry clover cv. Palestine was significantly more depressed than that of the other strawberry clover accessions evaluated (54% vs 73% of growth achieved under non-saline conditions), highlighting an opportunity for further cultivar development.

Strawberry clover is well known to have waterlogging tolerance (root-zone hypoxia or even anoxia) superior to that of many other perennial forage legumes (Rogers *et al.* 2009; Stevenson *et al.* 2017; Striker and Colmer 2017). A review by Striker and Colmer (2017) of the published literature found that moderate waterlogging induced growth reductions of <25% for strawberry clover, 35% for white clover, and >50% for both lucerne and red clover. Tiver (1954) reported intraspecific variation in the winter waterlogging tolerance of strawberry clover, attributing the greater tolerance of cv. Palestine to its superior winter growth potential. More recent studies have shown the development of aerenchyma and both adventitious and lateral roots underpinning strawberry clover's ability to avoid the oxygen deficit incurred by waterlogged conditions (Rogers and West 1993; Rogers *et al.* 2009). Such root morphological responses have also been observed in strawberry clover in response to the co-occurrence of salinity and waterlogging stress (Rogers and West 1993; Fig. 3). Under the combined stresses, root porosity (aerenchyma) of strawberry clover has been shown to be higher than under waterlogging stress in isolation (11.5% vs 5.8%; Rogers and West 1993). This greater root porosity may be a response to the increased oxygen demand of energy-dependent transport processes responsible for the exclusion of Na^+ and Cl^- from the shoot (Teakle *et al.* 2007).

Genetic diversity for salinity tolerance has been found within the species at various growth stages including germination, early seedling growth and mature vegetative growth (Schachtman and Kelman 1991; Rumbaugh *et al.* 1993; Rogers *et al.* 2009). Similarly, Stevenson *et al.* (2017) and Andersone-Ozola *et al.* (2021) identified strawberry clover genotypes with greater waterlogging tolerance than the current commercial cv. Palestine. Although the abovementioned studies suggest potential to develop strawberry clover cultivars that are more salinity and waterlogging tolerant than Palestine, other studies have reported contrasting findings (Craig 1994), and selection of plants with superior salinity tolerance has proved difficult (Gauch and Magistad 1943; Rumbaugh *et al.* 1993). Despite this, interest remains in selection for strawberry clover genotypes with increased

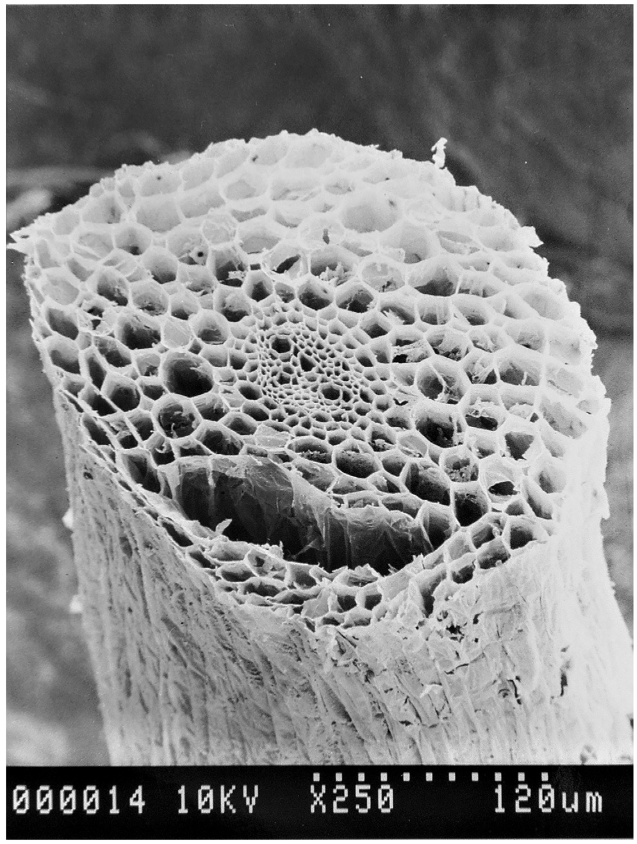

Fig. 3. Electron micrograph of strawberry clover root cross-section. Micrograph taken after 15 days of hypoxia at 60 mM NaCl, showing the development of aerenchyma (bottom section) as an adaptation to the waterlogged conditions (Rogers and West 1993).

salinity and waterlogging tolerance (McDonald *et al.* 2005; Nichols *et al.* 2008), so that better adapted and more productive genotypes are available for saline land. Such genotypes are critically needed, owing to the current absence of perennial forage legumes suitable for highly saline and waterlogged soils (winter, 0.8–5.0 dS/m; summer, 30.8–36.2 dS/m) (Nichols *et al.* 2008). Breeding programs also need to ensure that selected genotypes not only survive in these environments but also produce sufficient herbage to justify their sowing and establishment costs (Rogers *et al.* 1997*b*; Boschma *et al.* 2008; Nichols *et al.* 2008).

Heat (supraoptimal temperature) tolerance

No published research has quantified the heat tolerance of strawberry clover. However, it can be presumed to tolerate supraoptimal ambient temperatures (i.e. ≥30°C) based on its prevalence in environments where ambient temperatures often exceed 40°C (Frame 2004). Further research is required to evaluate whether strawberry clover has greater heat tolerance than other perennial legume species. The need for such research is further validated by the fact that, whereas red clover occurs in such environments, it is relatively sensitive to supraoptimal temperatures compared with other common temperate perennial pasture species (Langworthy *et al.* 2018). Claims of intraspecific variation in the temperature sensitivity of strawberry clover require such research to evaluate a range of strawberry clover genotypes (Duke 2012). Because many of the Australian regions where strawberry clover is cultivated for its salinity and waterlogging tolerance are characterised by hot summers, identification of genotypes with superior heat tolerance will be beneficial to the grazing industries in these regions.

Drought tolerance

Strawberry clover is a more drought-tolerant perennial *Trifolium* species than white clover (Dear *et al.* 2003; Milne 2011). During short periods of soil moisture deficit stress (≤54 days), studies under glasshouse and field conditions have shown strawberry clover's superior capacity to maintain leaf production and functionality relative to red and white clovers (Dodd and Orr 1995; Hofmann *et al.* 2007). Although the glasshouse study of Hofmann *et al.* (2007) failed to confirm the mechanisms underlying this tolerance, strawberry clover was noted to maintain higher leaf water potential, net photosynthesis and transpiration rate than white clover during a drying cycle. Over longer periods of soil moisture deficit (84 days), the three species (strawberry, red and white clovers) exhibited almost complete above-ground tissue senescence with very limited capacity to resume herbage production when irrigation was applied to alleviate stress conditions (Dodd and Orr 1995). On the basis of these studies, further investigation is warranted of strawberry clover for inclusion in temperate perennial pastures subject to intermittent periods of soil moisture deficit or in areas where irrigation is limited by water restrictions. Strawberry clover's advantage will most likely be targeted at environments where other constraints (notably waterlogging) impede the use of more drought-tolerant temperate perennial legumes such as lucerne (Dodd and Orr 1995; Bouton 2012).

Sowing rate and cost of seed

Relatively few management guidelines are available that are specific to strawberry clover, with management often presumed to be the same as for white clover. Sowing rates recommended for strawberry clover are 0.5–1.0 kg bare seed/ha when sown as a component in a mixture, 1–2 kg bare seed/ha when sown alone under dryland conditions, or 2–4 kg bare seed/ha under irrigation (Lattimore and McCormick 2012). Owing to differences in seed size, a sowing rate of 4 kg/ha strawberry clover was calculated by Hayes *et al.* (2022*a*) to deliver an approximately equivalent seeding density of white clover at 2 kg bare seed/ha, red clover at 5 kg bare seed/ha, or lucerne at 8 kg bare seed/ha, unless there was a factory coating on seed, which diminishes seeding density substantially. This puts the seed cost of strawberry clover into some context. A survey by the authors of three seed retailers across southern Australia showed that seed costs of strawberry clover were almost double those of white clover. If strawberry clover is to be sown at double the rate of white clover to achieve equivalent plant density, the farmer could be paying around four times the cost for seed to include strawberry clover rather than white clover. Morley (1963) suggested that one limitation to the broader utilisation of strawberry clover was seed cost: 'There seems no good reason why seed yields cannot be as high as those of white clover, and costs about the same, if care is taken to provide sufficient honey bees at flowering time'. It would seem that little progress has been made on this front in the last 60 years, and it is likely to be a contributing reason for lower areas of strawberry clover sowings.

Grazing management and forage conservation

Owing to its prostrate growth habit, strawberry clover is rarely used in forage conservation (Forde *et al.* 1981). There are several reports of it tolerating continuous, close grazing (Raguse *et al.* 1971; Forde *et al.* 1981), but few studies have been conducted to test the optimal grazing regime for this species. Raguse *et al.* (1971) included strawberry clover and white clover, along with cocksfoot and perennial ryegrass, in a grazing study in California where mixed pastures were grazed either continuously or in rotation by steers. The authors concluded that strawberry clover was the only species to respond positively to the continuous grazing regime. However, their study was unable to separate the confounding effects of competition from the different grazing regimes. The authors postulated that the reduced shading of strawberry clover by companion species in the continuous grazing treatment may have aided its performance. Further work is needed to understand the response of pure strawberry clover swards to different grazing regimes.

Strawberry clover persists largely through stolons, although recruitment from seed is also possible. In white clover, frequent defoliation of plants in pots depleted stores of non-structural carbohydrates, threatening plant survival (Singh and Sale 1997*a*), and effects were more extreme under low soil P fertility (Singh and Sale 1997*b*). If strawberry clover responds similarly on account of its stoloniferous growth habit, this species may also benefit from rotational grazing that allows periods for recovery of carbohydrate reserves and maximises stolon development. Continuous close grazing, especially by sheep, may reduce strawberry clover persistence in the long term by reducing stolon development. It may also reduce seedling recruitment, whereby flowers are continually grazed by livestock before they have a chance to set seed. Further work is needed to improve understanding of the factors affecting persistence and recovery of strawberry clover under different grazing regimes.

Forage quality

Crude protein (CP) concentrations in strawberry clover range between 13% and 26%, depending on maturity and environmental conditions. Kenny and Reed (1984), Norman *et al.* (2021) and Stutz *et al.* (2023) found that protein content decreased substantially with maturity and floral development, presumably because of the decline in the leaf: stem ratio with maturity (Minson 1980). In the comparative experiment of Norman *et al.* (2021), strawberry clover had higher CP content at the vegetative stage than 29 other legume species/accessions, and had CP content at the flowering stage similar to or higher than white and red clovers, although lower than lucerne. At the mature stage, the CP content in strawberry clover herbage was considerably lower than in all of the lucerne and red clover cultivars, as well as white clover cv. Storm (Norman *et al.* 2021). By contrast, Stutz *et al.* (2023) showed that strawberry clover had a similar protein content to white clover across a range of vegetative stages.

Norman *et al.* (2021) found that the acid detergent fibre content of strawberry clover at the vegetative stage was not significantly different from that of white clover (cv. Storm), sulla (*Hedysarum coronarium* L.), birdsfoot trefoil (*Lotus corniculatus* L.) and sainfoin (*Onobrychis viciifolia* Scop.) and was lower than that of lucerne. Stutz *et al.* (2023) also found strawberry clover to be similar to white clover cultivars with respect to neutral detergent fibre content.

There is a paucity of published literature regarding the metabolisable energy (ME) content of strawberry clover. Norman *et al.* (2021) measured the cumulative energy production (GJ ME/ha) for 30 accessions of perennial legumes over a series of successive cuts over a 12-month period. Strawberry clover had greater cumulative energy production than red clover (cvv. Rubitas and Tuscan), but lower than all of the white clover, sulla and lucerne cultivars. Norman *et al.* (2021) suggest that the cumulative energy of strawberry clover may become more similar to other commonly used legumes after the end of the second autumn; therefore, we recommend more long-term comparative studies that measure metabolisable energy over an extended period of time.

Andrew and Robins (1969) found strawberry clover had greater concentrations (% of DM) of chloride (0.43–2.50%), potassium (K) (0.54–3.93%), nitrogen (4.26–0.51%) and sodium (0.37–0.82%), and lower concentrations of magnesium (0.20–0.23%) and P (0.35–0.51%), than white clover and lucerne under several K fertiliser regimes. Micronutrient concentrations in strawberry clover were similar to the ranges in red clover and lucerne collated by Kao *et al.* (2020), except for boron concentration, which was found to be higher in strawberry clover than in both of the other species. Iron concentration was higher, and zinc lower, in strawberry clover than in lucerne. We recommend that collection of more data regarding the micronutrient profile of strawberry clover should be a research priority, so that producers and consultants can understand better the nutritional effects of using strawberry clover in pastures.

Overall, these data suggest that in terms of protein, acid and neutral detergent fibre, and mineral contents, strawberry clover can provide an alternative nutritionally similar to white clover. However, it is important to note that all data were from cv. Palestine, and all but one of the studies were conducted in Australia. Nutritional composition is known to be affected by environmental factors (Givens *et al.* 2000) and can vary widely between cultivars (e.g. Norman *et al.* 2021). Therefore, measuring nutritional composition of strawberry clover grown in other environments and from a variety of cultivars is a research priority for achieving better understanding of the nutritional composition of strawberry clover.

Anti-nutritional factors

As with many salt-tolerant species, strawberry clover has an enhanced ability to take up contaminant metals (Lutts and Lefèvre 2015). Cadmium (Cd) is a contaminant found in many P fertilisers, and thus has accumulated in many pastures that have had recurrent P fertiliser application (Langlands *et al.* 1988). When Cd is accumulated in the liver and kidneys of sheep and in offal at concentrations that exceed guideline limits, the organs must be disposed of, reducing the production value of the carcass (Langlands *et al.* 1988). Strawberry clover has been found to take up Cd to a greater extent than red clover, crimson clover (*T. incarnatum* L.) and white clover, but to a lesser extent than lucerne (Stafford *et al.* 2016).

Bloat (ruminant tympany) is a common disorder of livestock, particularly cattle grazing lush, legume-dominant pastures (Brightling 1994). It is reported to be a particular risk in pastures dominated by white or red clover, the foliage of which is low in condensed tannins that bind to soluble proteins and prevent the formation of rumen foam (Lane *et al.* 2000). Strawberry clover is rarely flagged as a high-risk forage for bloat (Frame 2005), although this may reflect a lower incidence of pastures with high strawberry clover content. The bloat potential and occurrence of condensed tannins in strawberry clover has been little studied. Redgut (intestinal torsion) is another common disorder particularly in sheep, caused by grazing highly digestible, legume-dominant pastures (Gumbrell 1997). Few instances have been reported in the literature of redgut caused by strawberry clover; however, this may also reflect a lower incidence of strawberry clover dominant pastures. Further studies are needed to establish both the bloat and redgut potential of strawberry clover.

The herbage of many common legume species contains phytoestrogens, which can lower the fertility of the grazing flock or herd (Reed 2016), yet the risk posed by strawberry clover is uncertain. Surprisingly, in a screening of the herbage of 100 *Trifolium* species for oestrogenic isoflavones, Francis *et al.* (1967) did not include *T. fragiferum*. Herbage of *T. neglectum* was included in that study and is a species sometimes considered a synonym of *T. fragiferum* (Forde *et al.* 1981); it was not reported to contain high oestrogenic isoflavone concentrations (Francis *et al.* 1967). Further research is required to determine the levels of phytoestrogens in strawberry clover. Notwithstanding, most of the risks posed by anti-nutritional compounds in legumes can be managed by growing the species in mixtures to provide diversity in the diet of grazing ruminants.

Rhizobia and nitrogen fixation

Seeds of strawberry clover are recommended to be inoculated with *Rhizobium leguminosarum* bv. *trifolii* strain TA1 (Group B) (Drew *et al.* 2012). In studies by Rigg *et al.* (2021), strawberry clover cv. Palestine formed effective nodules with both TA1 and WSM1325 (Group C) rhizobial strains, but formed ineffective symbioses with rhizobial strains used for other perennial legumes. The cross-host compatibility observed in strawberry clover cv. Palestine may be an advantage in many environments of south-eastern Australia where older Group C rhizobia strains are endemic owing to a long history of subterranean clover use (Rigg *et al.* 2021). There are no data available to inform the cross-host rhizobial compatibility of other strawberry clover cultivars, and further studies are needed.

Use in mixtures

The lower productive potential of strawberry clover than of other legumes suggests that it is unlikely to become a dominant species encroaching in a significant way on the mainstream perennial legume species white clover, red clover and lucerne. However, justification exists for the inclusion of strawberry clover as a component of pasture mixtures. First, it is a perennial legume. Agriculture in southern Australia relies heavily on self-regenerating annual legumes (Nichols *et al.* 2012), but they often struggle to compete for light and water with perennial pasture species, especially beyond the year of sowing, resulting in reduced persistence (Dear *et al.* 1998). The perennial habit of strawberry clover does not require annually set seed and regeneration of seedlings for persistence, and this provides a competitive advantage over self-regenerating legume species. Second, perennial legumes such as strawberry clover can provide more early autumn feed than annual legumes because they already have extensive root systems and above-ground branches when annual species are still establishing. Third, perennial species such as strawberry clover provide increased options to establish a companion legume in spring-sown, perennial-based pastures. As demonstrated by Li *et al.* (2014), perennial pastures sown in autumn can include subterranean clover, whereas those sown in spring should be sown only to perennial species, owing to the inability of spring-sown subterranean clover to set seed and regenerate in subsequent years.

The superior heat and moisture stress tolerance of strawberry clover compared with red and white clovers is another advantage in mixtures. Vigorous perennial companion species such as phalaris or lucerne are known to exacerbate the apparent moisture deficit experienced by companion species (Dear and Cocks 1997; Dear *et al.* 2010), and this might be expected to diminish the persistence of profligate water users such as white clover (Norton *et al.* 2021). The lower productivity of strawberry clover may be an advantage in this scenario, by reducing the amount of tissue to be maintained under drought and reducing the competitive effects on other sward components that can drive overall pasture productivity. The extent to which strawberry clover can endure this competition requires further testing across a diversity of environments. The prostrate habit of strawberry clover also offers advantages in increasing groundcover, which is sub-optimal in lucerne pastures (Hayes *et al.* 2018). Such increased groundcover is likely to increase water infiltration over summer and reduce soil temperatures, both of which are likely to enhance lucerne persistence and productivity (Hayes *et al.* 2021). The case for including strawberry clover in mixtures with lucerne offers additional advantages where lucerne density is reduced through periodic waterlogging (Dear *et al.* 2010).

Other uses

Strawberry clover has a flowering window quite similar to white clover, which can last from mid-spring to autumn under favourable conditions (Dodd and Orr 1995; Somerville 2019). Honey bees have been noted to forage on flowers of this species (Forde *et al.* 1981), but its value for honey production remains in question. It is noted as a species of only moderate value to apiarists across south-eastern Australia (Somerville 2019), which may simply reflect the fact that it has not traditionally been grown widely. There are several reports in the literature that the flowers of strawberry clover are 'extremely attractive to honey bees for both nectar and pollen' (McGregor 1976), but data quantifying this to provide comparisons with other, more studied species are scarce. As a largely cross-pollinating species in which seed production has been suggested to increase almost 3-fold where honey bees are actively foraging (Morley 1963), there is little doubt that strawberry clover flowers offer rewards for foraging honey bees, and are assumed to be of similar quality to white clover flowers (Somerville 2019). However, the timing, quantity and quality of nectar and pollen from this species has not been quantified.

Strawberry clover provides excellent groundcover and is a useful component of lawn or turf mixtures. In fact, cv. Fresa was selected for its low, dense habit and was developed as a low-maintenance groundcover for use in lawns (Baltensperger *et al.* 1982; Baltensperger and Gaussoin 1984). It may also be useful in vineyards and orchards where low biomass production is an advantage, or on sporting fields, particularly where drainage or irrigation systems are imperfect, because it can tolerate extremes of too much or too little water better than many other species. Its year-round growth habit also makes it a useful addition in sporting fields; it is less affected by frost than kikuyu (*Cenchrus clandestinus* Hochst. ex. Chiov. syn. *Pennisetum clandestinum*) or other C_4 grass species often used, thereby maintaining an aesthetically pleasing green appearance throughout the year. Strawberry clover was also advocated by Whittet (1964*b*) for planting along irrigation channel banks with kikuyu to control weeds and limit erosion caused by livestock, highlighting the value of this species in a diversity of settings.

Pest and disease issues

Pasture pests and diseases can contribute to the poor persistence of legumes within a mixed pasture (Allen 1989; Irwin 1989). However, there are few published reports concerning the economic impact of pests and diseases on temperate perennial legume species other than white clover, red clover and lucerne (Allen 1989; Irwin 1989; Jones 2013).

Major pests considered across southern Australia that can negatively impact strawberry clover production and persistence are likely to be similar to those affecting white clover (Allen 1989). These include redlegged earth mite (*Halotydeus destructor*); blue oat mite (*Penthaleus major*); lucerne flea (*Sminthurus viridis*); root feeding scarabs (*Sericesthis* spp.); corbies, pasture web worms and related caterpillars (*Oncopera* spp.); pasture cockchafers (*Aphodius* spp.); cutworms (*Agrotis* spp.); native budworm (*Helicoverpa punctigera*); and bluegreen aphid (*Acyrthosiphon kondoi*) (Roberts *et al.* 1979; Allen 1989).

There have been limited screenings of disease-causing pathogens that impact strawberry clover in Australia (Buchen-Osmond *et al.* 1988; Jones 1996, 2013). The only record of a virus disorder occurring in strawberry clover in Australia is of *White clover mosaic virus* in Western Australia (Buchen-Osmond *et al.* 1988). Several fungal diseases have been identified as occurring in strawberry clover, including *Fusarium* spp. (Kellock *et al.* 1978), and pepper spot caused by the fungi *Leptosphaerulina trifolii*, *Colletotrichum trifolii*, *Pleospora herbarum* and *Pseudopeziza trifolii* (Shipton 1967).

Soil nematodes may significantly reduce perennial legume performance by reducing root growth and nitrogen fixation, and by stunting both leaf and stolon growth. Strawberry clover has been reported to be susceptible to root-knot

Table 2. Growing rules developed for perennial pasture species divided into suitability classes.

Suitability rating	Species	Soil depth (mm)	Soil pH_{water}	ECse (dS/m)	Drainage	Stone (%)	AAR (mm)
Well suited	Lucerne	>800	>6.2	<3.0	WD, EWD	<10%	>500
	White clover		>6.0	<3.0	MWD, WD	<10%	>700
	Red clover		>6.0	<4.0	WD, EWD	<10%	>650
	Strawberry clover		>6.2	<6.0	PD, ID, MWD, WD	<10%	>600
Suitable	Lucerne	500–800	5.7–6.2	3.0–4.5	MWD	10–20%	350–500
	White clover		5.5–6.0	3.0–4.5	EWD, ID	10–20%	650–700
	Red clover		5.5–6.0	4.0–5.0	MWD	10–20%	600–650
	Strawberry clover		5.7–6.2	6.0–7.0	VPD, EWD	10–20%	600–650
Moderately suitable	Lucerne	300–500	5.2–5.7	4.5–5.5	ID	20–50%	300–350
	White clover		5.0–5.5	4.5–5.5	PD	20–50%	600–650
	Red clover		5.0–5.5	5.0–6.0	IP	20–50%	500–600
	Strawberry clover		5.2–5.7	7.0–8.0		20–50%	500–600
Unsuitable	Lucerne	<300	<5.2	>5.5	VPD, PD	>50%	<300
	White clover		<5.0	>5.5		>50%	<600
	Red clover		<5.0	>6.0	VPD, PD	>50%	<500
	Strawberry clover		<5.2	>8.0		>50%	<500

Soil depth relevant only to lucerne. Soil pH and electrical conductivity of saturated extract (ECse) in 0–150 mm soil depth. EWD, excessively well drained; WD, well drained; MWD, moderately well drained; ID, imperfectly drained; PD, poorly drained; VPD, very poorly drained. Stone abundance recorded as visual estimate of percentage stones >200 mm on the soil surface. AAR, average annual rainfall.

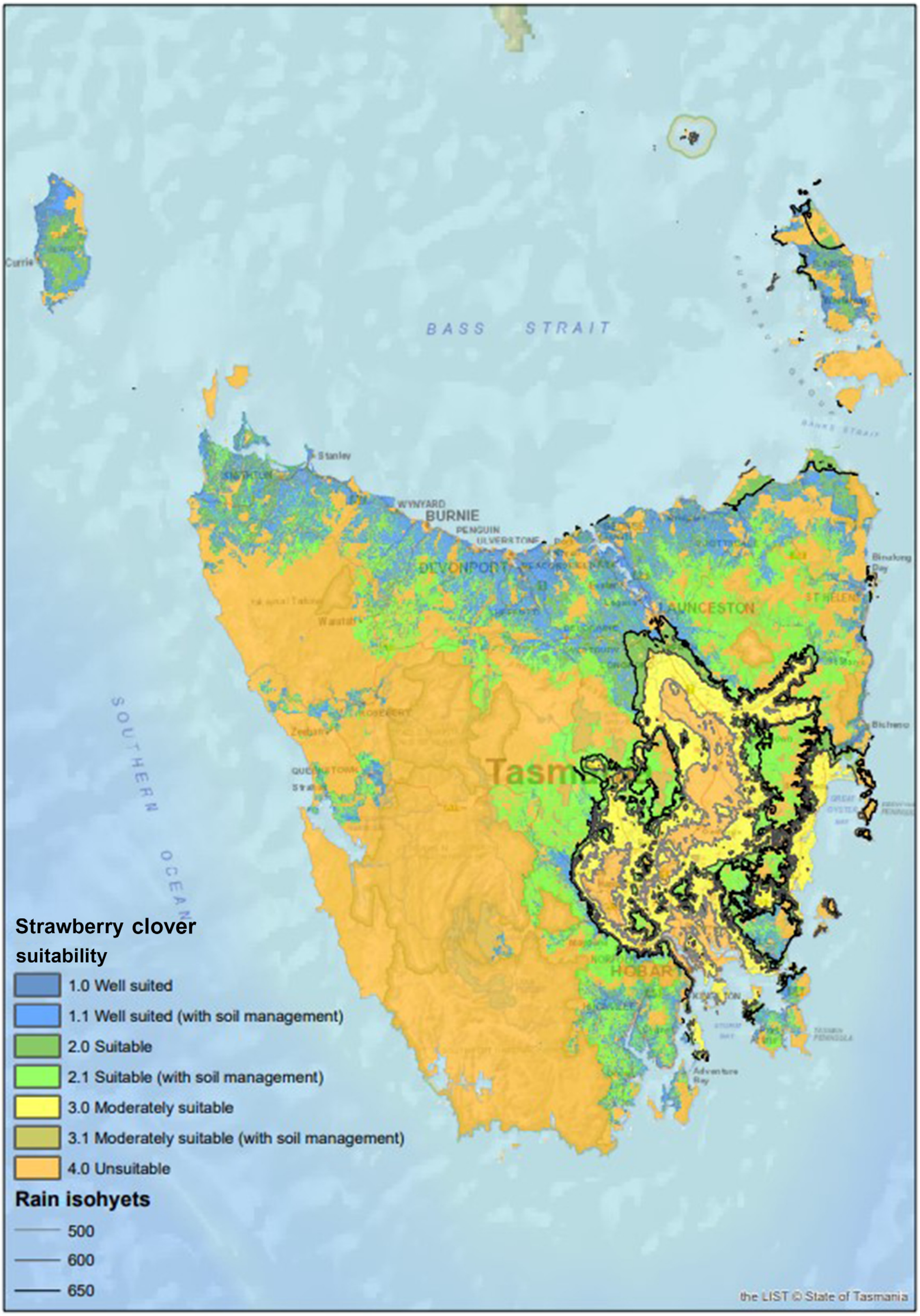

Fig. 4. Suitability of strawberry clover to pastures across Tasmania, developed using growing suitability rules outlined in Table 2.

Fig. 5. Niche areas where the suitability class for growing strawberry clover is either 'well suited' or 'suitable', and where lucerne, white clover and red clover are moderately suited or unsuited in pastures across Tasmania. Developed using growing suitability rules outlined in Table 2.

nematodes (*Meloidogyne* spp.) (Shipton 1967; Quesenberry *et al.* 1986) and *Pratylenchus thornei* (Grandison and Wallace 1974).

The use of resistant cultivars to combat both pasture pests and disease-causing pathogens is likely to be the best long-term, low-cost option. However, because little published information exists for strawberry clover, there is an initial need to determine the relevant benchmarks for pasture pest and disease incidences, and yield losses caused by the most prevalent pests and diseases affecting the species. This will inform the selection of pests and diseases for which to conduct resistance screening programs among current cultivars and diverse germplasm, and the need for future breeding programs for pest and disease resistance.

Climate and soil recommendations

Using the information compiled in this review, we have suggested growth suitability rules for strawberry clover (Table 2) for the purpose of mapping its suitability in Tasmania, Australia (Fig. 4). These rules include both soil and rainfall parameters developed for land suitability mapping (Kidd *et al.* 2015). To determine the niche areas where strawberry clover might have superior adaptation over other perennial legumes, growth suitability rules have also been suggested for lucerne, white clover and red clover (Table 2). These niche areas for Tasmania are highlighted in Fig. 5. Although strawberry clover has broad adaptation, the other perennial species will likely be more productive. Nonetheless, the niche areas where strawberry clover may be more suitable than the other species is not insignificant. Similar growth suitability maps for strawberry clover could be drawn for the other states of Australia and, indeed, for other parts of the globe.

Future research and conclusions

Strawberry clover has a clear advantage over other temperate perennial legume species in environments prone to waterlogging or to moderate salinity. Outside this niche, its potential zone of adaptation has hitherto been poorly defined. Strawberry clover seems unlikely to enjoy widespread adoption in areas with shallow and acidic soils, or in environments where white clover or subterranean clover are more productive (Kemp *et al.* 2002). Strawberry clover may be successful in high-rainfall 'cropping zone' environments such as those described by Li *et al.* (2008), although more evidence and research is required on drought tolerance. However, we acknowledge that strawberry clover is unlikely to match the productivity of lucerne in most environments. Therefore, the case for replacing lucerne with strawberry clover is not proposed unless for areas subject to waterlogging. Rather, we propose that a possible fit for strawberry clover in future pasture systems could be as a companion species with lucerne in semi-permanent pastures for grazing, for the following reasons:

- Both species are broadly suited to more fertile soils with mild levels of acidity.
- The lower yield potential of strawberry clover may make it a less competitive neighbour with lucerne than alternative legume species.
- The prostrate habit of strawberry clover promises many advantages for lucerne swards that are commonly plagued by low levels of groundcover (Hayes *et al.* 2018).
- The perennial habit of strawberry clover promises advantages over self-regenerating annual legume species that struggle to co-exist with lucerne in the long term (Dear *et al.* 2000; Dear *et al.* 2007).
- More productive cultivars of strawberry clover have yet to be developed; a less risky approach is to target it as a companion species to be grown in mixtures.

To our knowledge, no research has examined strawberry clover in mixtures with lucerne. One major question surrounding adding strawberry clover with lucerne is whether it can persist in the low soil moisture content environments that develop when lucerne dries the soil profile during drought conditions. Use of alternative spatial sowing arrangements may reduce this competition, although it may increase intraspecific competition if sowing rates are not reduced (Hayes *et al.* 2021). This would seem to be a high priority for future research to increase the utilisation of this important species and add value to contemporary production systems. In addition to the suggested improvement of waterlogging and salinity tolerance (Nichols *et al.* 2008, 2012), development of tolerance to acidic soils should be continued, but coupled with increased productivity. Further, the drought tolerance and recovery through vegetative stolon spread following periods of moisture deficit where white clover fails to persist requires examination. Strawberry clover remains an underutilised species, although new research and demonstration is required for this species to be adopted across a wider range of environments and grazing systems.

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