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Stocktake and analysis of legume evaluation for tropical pastures in Australia

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Abstract

There has been a large effort dedicated to the evaluation of a wide variety of sub-tropical and tropical pasture legumes in the past. This large body of information is very valuable for guiding any future legume development activities, yet much of this information was at risk of being lost. This project aimed to collate and store this tropical legume evaluation data and use this and knowledge from past researchers to recommend priority R&D approaches and activities for future pasture legume development. Together with retired pasture researchers, legume evaluation datasets were identified, prioritised, and collated into a database which captured over 180 000 data records collected from 567 sites across northern Australia. Using this large integrated dataset, high power statistical approaches were used to identify legume species which performed well across this large range of evaluation sites. Several species and genera were identified which warrant further investigation and further in-depth analysis of the database in species or genera of interest would be valuable. A gap analysis of commercially proven, underused and prospective legumes was conducted across the key production regions of northern Australia. A range of material was identified which could offer potential improvements in seed production, cold, drought or grazing tolerance compared to the current released varieties.

Executive Summary

The addition of legumes to tropical pastures has the potential to have large benefits for the productivity and profitability of beef production enterprises in northern Australia. This has long been recognised and a large effort has been made in the past to develop forage legumes suited to a range of environments and production systems in northern Australia. While some legumes have been extensively used, increasing the adoption of legumes into tropical grass-based pastures has been challenged by high costs and poor reliability of establishment, and variable persistence of legumes. Systematic evaluation and development of improved legumes has stalled over the past 10-20 years. However, there is renewed interest in reinvigorating these efforts to improve the range of legumes and/or develop new elite material available in northern pasture systems. Much of the past research by retiring pasture scientists is at risk of being lost, at the same time a great deal could be learnt from examining past legume evaluation efforts.

The objectives of this project were to:
1. Collate and store tropical legume evaluation data and knowledge from past and current legume evaluation (including the ‘grey’ literature); and
2. Review and analyse the information collated to establish the value proposition of renewed pasture legume evaluation and to recommend priority R&D approaches and activities.

This project brought together past and current pasture researchers to prioritise and collate past evaluation data on legumes for tropical pastures into a common database that can be used as a resource to guide future legume development activities. Over 180 000 records of evaluation data of pastures legumes from 567 sites in the tropics and subtropics were collated. Initial interrogation of this database with high power statistical approaches aimed to draw out species or taxon which performed well across a wide range of environmental conditions that could be candidates for further research. At the same time, drawing on expert opinion and knowledge a legume gap analysis was conducted across 12 production regions of northern Australia to identify where further legume development needs are greatest. This also aimed to identify priority genera, species and accessions that should be prioritised for further evaluation and/or potential commercialisation.

Statistical analysis across a range of past evaluation locations and conditions has revealed several tropical legume species that have higher productivity potential than commercially successful species. In particular, several *Desmanthus* species showed high levels of persistence and higher year 3 productivity than other species across a range of environments, indicating they many have wider potential for development. Some *Macroptilium* species also demonstrated wide potential, with *Macroptilium lathyroides* in particular, showing higher productivity levels in both year 1 and year 3 and performed relatively better than other species at locations with lower site yields. Some *Alysicarpus* species were found to increase their yield over time and to have amongst the highest yields in year 3, particularly in more favourable conditions. However, some care should be taken with wider interpretation of this species performance analysis, as all accession for a species are included. Further examination of variation within species or comparisons amongst individual accessions may reveal further information on genotype performance across the full set of evaluation experiments.

The region by region gap analysis of 1) commercially proven legumes, 2) of adapted commercially but not successfully or of widely adopted, and 3) prospective species identified significant gaps in adapted and commercially proven legume varieties in western Qld, southern Northern Territory and northern Western Australia. However, the value proposition for legume development targeted to those low-productivity environments is likely to be low. In other regions, a limited set of well accepted options are available but gaps in these array of legumes are evident and/or agronomic constraints or limitations restrict their uptake or wider adoption. Highest priorities for further legume development identified were i) legumes that persist in competitive grass pastures in the subtropical semi-arid inland, and sub-humid coastal hinterland, ii) legumes for clay soils in northern tropical

regions, iii) legumes for light soils (sandy and duplex) in inland subtropics, and iv) more robust ley legume options. Several species and accessions that have shown promise in past evaluation work and are thought to have attributes which improve on key limitations of commercial varieties but are not yet commercialized were identified in *Desmanthus*, *Stylosanthes, Macroptilium*, and *Aeschynomene*.

Overall, this report suggests there is still potential to make gains in the range and performance of legumes available for pasture systems in Northern Australia.

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1 Background

Australia's northern beef industry is facing some major challenges associated with the need to maintain enterprise profitability through improvements in productivity and reductions in costs of production (Gleeson et al. 2012). One area where large improvements in productivity might be achieved is through the use of improved or more intensive forage production systems where increased beef turn-off and enhanced marketing opportunities are possible. The addition of legumes to tropical pastures has been demonstrated to greatly improve animal productivity by overcoming seasonal protein deficiencies and supplying N to companion grasses. Augmenting pastures with legumes can increase annual live-weight gain by 25-30 kg/head, but can have some additional indirect benefits of improving pasture utilisation and improved weaning rate, which together can increase farm profitability by >85% (Ash et al. 2015).

The potential benefits of legumes for northern beef production systems has long been recognised (Davies And Eyles 1965). Hence, there has been a large effort dedicated to the evaluation of a wide variety of sub-tropical and tropical pasture legume germplasm initiated in the 1960s (Hutton 1970). These efforts have resulted in the release of many legume cultivars suited to a range of environments and production systems in northern Australia (Jones 2001). While some legumes have been integrated into pasture systems successfully (e.g. *Stylosanthes hamata*, *Stylosanthes scabra, Leucaena leucocephala*), wider incorporation of tropical legumes into pastures has been challenging. High costs and poor reliability of establishment, along with variable persistence of legumes are put forward by producers as significant constraints to wider adoption (Clements 1996).

Perceived diminishing returns on the R&D investment from further legume evaluation has seen this effort diminishing over the past 20 years. Consequently, over the past 10 years there has been no ongoing systematic approach to identifying and evaluating promising pasture legumes from the existing germplasm collection (>10,000 accessions). However, there is renewed interest from beef producers and the pasture seed industry in reinvigorating efforts to improve the range of legumes available in northern pasture systems. Lines of *Stylosanthes* and *Desmanthus*, with adaptation to environments currently devoid of sown pasture legume options, were recently identified from re-visiting abandoned pasture evaluation trials (some having been established as early as the mid-1970s) (Gardiner, pers. comm.; Peck pers. comm.). Other projects are also evaluating promising pasture legumes and grasses for the beef production systems of northern and central Queensland and are utilising a pool of promising legume and grass lines based primarily on a mix of opportunistic evaluation work and expert opinion (Cox, pers. comm). However, any longer-term investment in legume evaluation should be informed by the results of past systematic approaches.

A great deal could still be learnt from re-examining these past efforts in order to identify further opportunities and guide current and future directions and priorities for legume development. However, much of the information and knowledge resides with researchers who have left or are now leaving the workforce. Hence, this project aimed to make an effort to consolidate available data, information and knowledge before this is lost. The work further aimed to support the work initiated by Cook et al. (2005), which relied largely on the experience of a number of the same people (see www.tropicalforages.info).

The project reported here centred around a stocktake of the prior pasture legume germplasm evaluation in order to identify where opportunities and gaps in legume evaluation still exist. This involved bringing together past and present leaders of pasture legume evaluation from key pasture research agencies (CSIRO, NT and Queensland State Departments), as well as the pasture seed industry, to review past legume evaluation efforts, and identify key data sets to be collated. A database was developed to capture the extensive datasets that were obtained so that this might be a resource for future pasture development activities. Interrogation of these data along with expert opinion and knowledge were utilised to recommend priorities for further legume development for beef production systems in northern Australia.

2 Project objectives

1. Collate and store tropical legume evaluation data and knowledge from past and current legume evaluation (including the ‘grey’ literature);
2. Review and analyse the information collated to establish the value proposition of renewed pasture legume evaluation and to recommend priority R&D approaches and activities.

3 Methodology

3.1 Evaluation data identification

The first stage of the project involved a workshop that brought together 16 past and present pasture legume researchers (participants listed in Table 1) with the aim of compiling a prioritised list and associated information on the available (published and unpublished) data and information from past and current legume evaluation work. From this workshop a list of data sources, including grey literature, were prioritised to be collated in a comprehensive database. Requirements and attributes of the database were also recommended using information and characteristics of the existing Q Pastures (which uses dated software and has limited measurement data available) and Genetic Resources Information Network (GRIN) Global database used by many Genetic Resource Centres in Australia and worldwide.

Table 1. List of participants in project workshops.

Workshop 1 aimed at prioritising a list of legume evaluation datasets for collation, and workshop 2 aimed at analysing the gaps and opportunities for future legume development in northern Australia. Attendance at either workshop is indicated with a #.

Participant	Organisation	Role	Wkshp 1	Wkshp 2
Lindsay Bell	CSIRO	Pasture Sci.	#	#
Gary Bastin	CSIRO	Data management	#	
Justin Fainges	CSIRO	Data management	#	#
Trevor Hall	DAFQ	Pasture Sci.	#	#
Richard Silcock	DAFQ	Pasture Sci.	#	#
Kendrick Cox	DAFQ	Pasture Sci.	#	#
Gavin Peck	DAFQ	Pasture Sci.	#	#
Arthur Cameron	NT DPI	Pasture Sci.	#	#
Bruce Pengelly	Retired CSIRO	Pasture Sci.	#	#
Bruce Cook	Retired QDPI	Pasture Sci.	#	#
Bob Clem	Retired QDPI	Pasture Sci.	#	#
Harry Bishop	Retired QDPI	Pasture Sci.	#	
David Lloyd	Retired QDPI	Pasture Sci.	#	#
Chris Gardiner	JCU	Pasture Sci.	#	
Phil Anning	Retired QDPI/NTDPI	Pasture Sci.	#	#
Steve Hughes	SARDI	Genetic Resources	#	
Ross Darnell	CSIRO	Data analyst		#
Suzanne Boschma	NSW DPI	Pasture Sci.		#
Allan Mudford	PGG-Wrightsons Seeds	Seed Industry		#
Greg Flavell	Heritage Seeds	Seed Industry		#
Iain Hannah	Agrimix	Seed Industry		#
Nick Kempe	Agrimix	Seed Industry		#

Over 100 data sources were identified with potential information that might be included in the database. The highest priority set (n=22) included focussed legume evaluation work conducted in COPE (Coordinated Pasture Evaluation in northern Australia) (Pengelly and Staples 1995), BULS (Back-Up Legumes for Stylos) (HG Bishop and Hilder 1999), Legumes for Clay Soils (RL Clem and RM Jones – NAP3.103), NTDPI plant introduction and technical reports (AG Cameron 1989) and NAPLIP- Queensland Component (National Annual Pasture Legume Improvement Program) (DL Lloyd and B Pengelly – CSA3) – much of this data is only available in hard copy reports and has not been published. Data presented in a range of scientific publications (primarily *Tropical Grasslands* and *Australian Journal of Experimental Agriculture*) and CSIRO, QDPI and NTDPI technical reports or memorandums were also digitised and included (a full list of published data sources used is provided in the references). The data collated primarily focussed on measures of plant productivity and persistence in field evaluation activities, but some data on additional agronomically significant traits such as seed production, frost and disease tolerance and palatability were also included when readily available (see Table 2 for more detail).

3.2 Database design and structure

A relational database was constructed in SQL to collect data on the evaluation of legumes for tropical pasture systems over the last 40 years. The database was constructed to store a range of key agronomic data and allow multi-site and large scale analyses. The database was also constructed so that queries can be run to allow users to extract specific data from the database. For example, data available in the database can be extracted using queries associated with singular or combinations of legume taxonomy (Genus, Species or Accessions), locations or latitude and/or longitude boundaries, data source or measured trait. The structure of the relational database is shown in Figure 1. In brief the data-base links tables of information describing taxonomy of species, accessions/lines or cultivars, agronomic measurements with their associated trait and method of measurement, and site characteristics and location.

The database has been designed to be interrogated using a set of structured queries that allow users to access data of interest. Database design is also compatible with current database systems utilised by Genetic Resource Centres in Australia and internationally (e.g. GRIN). User-friendly systems for queries and reports have been developed should the database be made publically available in the future.

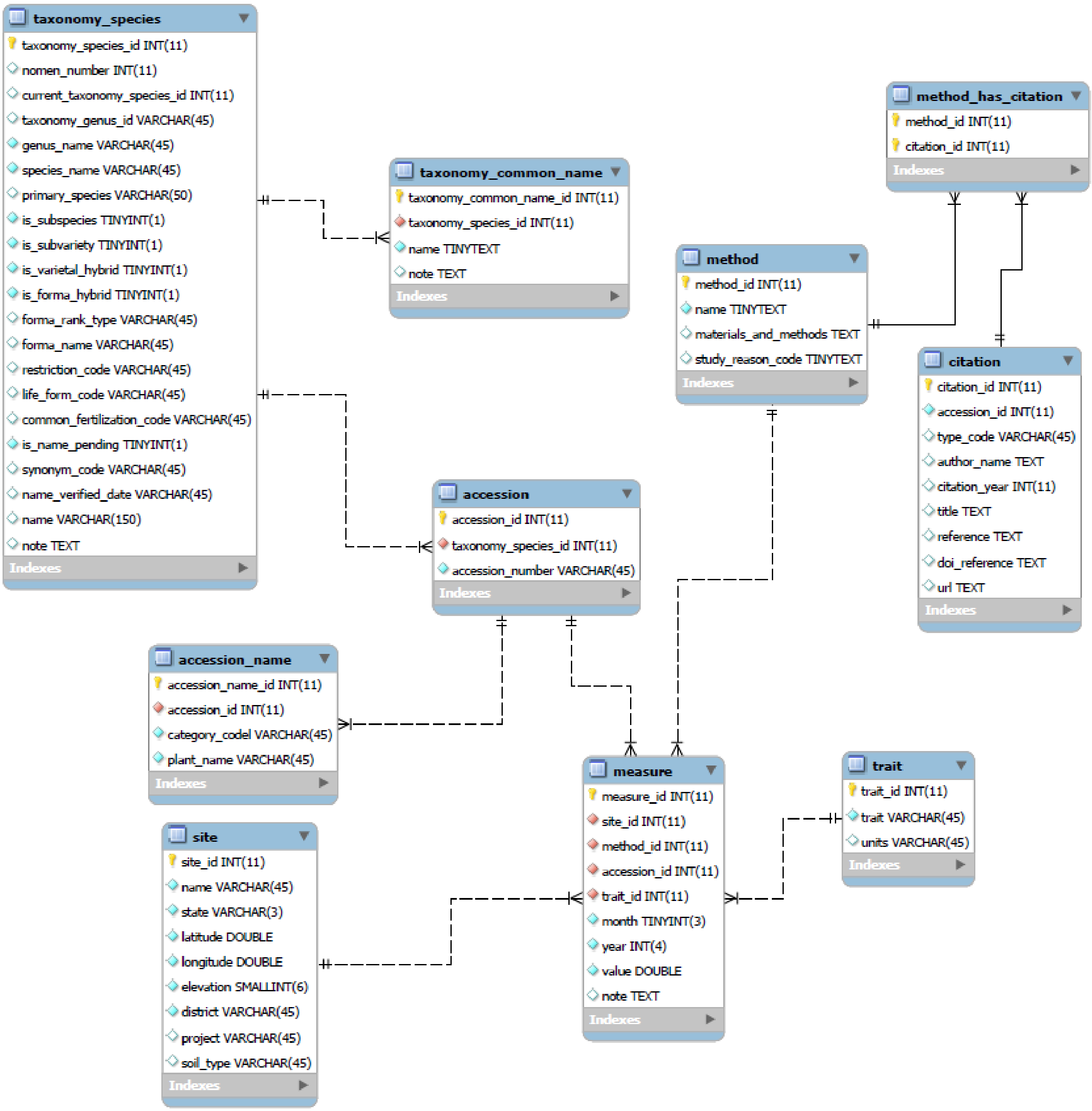

Figure 1. Relational database structure showing linkages between key elements such as taxonomic information, accession information, experimental site characteristics, traits and their measurements and methods of measurement.

The database collates over 180 000 records of past legume evaluation on 950 species, including 7 000 accessions and 567 individual sites.

3.3 Database summary statistics and scope

Upon completion of the project, the database contained evaluation measurements on 950 putative species, 7061 accessions/cultivars, at 567 sites (site may include the same location but different soil/projects), on up to 25 different traits. In total over 180 000 measurements were captured. The majority of data captured were for the traits biomass yield or biomass yield ratings, establishment counts and persistence ratings (Table 2). Nonetheless important information associated with forage or grazing quality and palatability (leafiness, dry season green, palatability), seed production and regeneration (seed yield and seed yield rating, rate of spread, seed yield per plant, seed count) and abiotic and biotic tolerance (frost tolerance, grazing/cutting tolerance, fire tolerance and disease tolerance) are also included for some accessions (see Table 2).

Table 2. Summary of the number of measurements recorded per trait in the legume evaluation database.

Trait	No. of records
Biomass Yield Rating	31 019
Establishment	23 532
Persistence	12 670
Biomass Yield	11 864
Height	11 863
Dry Season Green	11 245
Leafiness	11 219
Competitive Ability	9 042
Seed Yield Rating	8 007
Frost Tolerance	7 629
Rate of Spread	7 543
Grazing/Cutting Tolerance	7 342
Drought Tolerance	6 644
Vigour	5 801
Regeneration	5 264
Fire Tolerance	4 939
Seed Yield	3 564
Palatability	370
Seed Yield Per Plant	314
Yield Per Plant	55
Seed Count	52
Disease Tolerance	35

Table 3 summarises the projects which provide the largest datasets contained in the database. Clearly COPE (Coodinated Plant Evaluation in Northern Australia), is the largest and this work was undertaken over several years (3-8 years) at 12 locations in northern Australia (Pengelly and Staples 1995). Northern Territory plant introduction evaluation is also a large dataset (Cameron 1986; 1992; Cameron and McKosker 1986). However, this also includes information on performance of grasses and other non-legumes, which were difficult to remove from the data provided. The other key datasets originate from NAPLIP (National Annual Pasture Legume Improvement Program) (Nichols *et al.* 2007), BULS (Back-Up Legumes for Stylos) (Bishop and Hilder 1999) and a range of QDPI (now DAFQ) projects. A large amount of additional data, with no associated project name is also included (over 6 500 measurements). Structured data from the Kimberley region of Western Australia was unavailable to the project team.

Table 3. Summary of the number of measurements recorded per major project in the legume evaluation database

Project name/code	No. of records
COPE	34 322
NT Plant Introduction Performance	22 032
NAPLIP Nursery (Temperates)	13 477
BULS	6 033
Cle P4 WR (SW Qld)	5 906
Exotic and Naturalised Poly Medics	5 574
Mba P39.28 MR (Narayen)	5 145
DAQ 51 (Darling Downs)	4 532
Mba P39.01 MR (Southedge Research Station)	4 448
Legumes for Clay Soils	4 106
Mba P39.21 MR (Springmount)	3 876
Tba P168 WR	3 763
INTRODUCED PASTURE SPECIES SCREENING	3 459
Mba P39.12 MR (Mutdapilly)	3 166
Mba P39.23 MR (Lochwall)	3 115
Tba P164 AB (Temperates)	2 923
Edye – Stylo screening & evaluation	2 744
Trifolium evaluation	2 303
Tba P165 AB	1 573

The legume genera that have the largest number of recorded observations contained in the database are shown in Table 4. Amongst this group 70% of the recorded observations are for tropical/warm-season legumes, while 25% of recorded observations are for the temperate/subtropical genera, *Trifolium*, *Medicago*, *Hedysarum* and *Pisum* which have been tested as a cool-season component in pastures or cool-season forage crops, primarily in the subtropics. The most studied tropical, warm season legume genera are *Stylosanthes*, followed by *Aeschynomene* and then *Macroptilium* and *Desmanthus*. Maps showing the distribution and intensity of evaluation across northern Australia for 18 of these legume genera are shown in Appendix A. Most genera have received evaluation over a wide range of environments, with the exclusion of far western regions of Queensland and southern Northern Territory.

Table 4. Summary of the number of measurements recorded per legume genus in the legume evaluation database

Genus	No. of records
Trifolium	18 029
Stylosanthes	13 928
Aeschynomene	11 011
Medicago	9 773
Desmanthus	8 818
Macroptilium	7 495
Hedysarum	7 098
Glycine	6 710
Vigna	6 073
Centrosema	5 834
Clitoria	4 485
Desmodium	4 470
Alysicarpus	4 350
Arachis	2 581
Pisum	1 955
Macrotyloma	1 883
*Lotononis**	1 777
Cassia [Φ]	1 769
Rhynchosia	1 741

* mostly now ascribed to *Listia*

[Φ] mostly now ascribed to *Chamaecrista*

4 Meta-analysis of legume evaluation data

A meta-analysis using high power statistical methods was undertaken to explore genotype by environmental (G x E) interactions to explore relative performance of forage legume species using the data collated in the database. Further analysis at the accession level are possible but because of the unbalanced nature of the data would require more focussed analysis within a species or genus. Three data sets were analysed separately for this report. The first analysis examines the data from COPE experiments (i.e. 12 sites in Queensland), the second all evaluation data collected from tropical legumes sowing, and thirdly data from experiments that included temperate legumes in tropical and subtropical climates. The analyses focussed on which species were "standouts", those that persisted and produced well across a range of locations and those that were persistent and productive in specific environments. The data stored on this database consisted of averages for accessions at a particular site at a particular harvest time, so it was not possible to estimate inter-plot variability. Not all accessions were grown at all sites so the analysis is moderately unbalanced. Hence, for these analyses it was necessary to reduce the data set for analyses based on the number of sites at which a species was grown and the number of accessions grown at a particular site. Data were omitted if a species occurred at fewer than 10 sites and if fewer than 5 accessions for that species were represented.

The analysis to determine the genetic response to environments was performed using the R (R Core Team 2015) packages ASReml (Butler 2009a) and MYF (Butler 2009b). We follow the analysis shown in Smith (2015) for cases in which there were sufficient species data to perform these analyses. In addition, we presented the results using the Finlay-Wilkinson (FW) approach to illustrate genetic by environmental effects (Finlay & Wilkinson, 1963). The interpretation of the FW plots is illustrated in Figure 2.

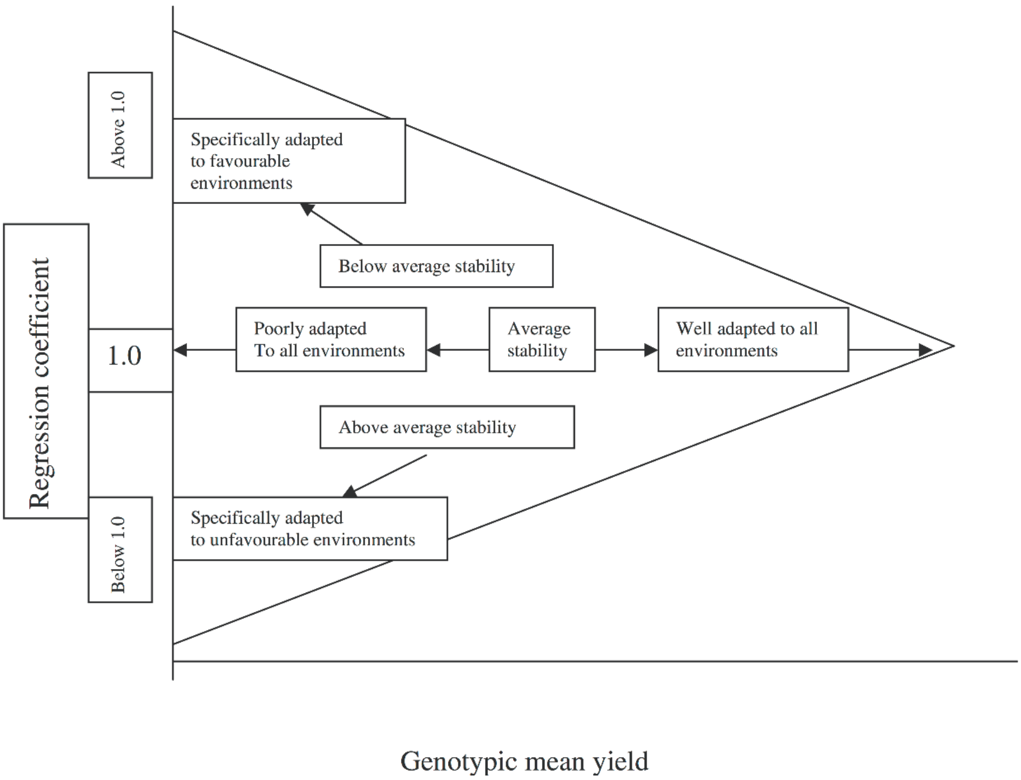

Figure 2. Interpretation guide for Finlay-Wilkinson plots for yield and persistence.

The genotypic mean across all sites (x-axis) indicates how a species or accession performs on average across all environments; genotypes (species or accessions) farther to the right have higher performance scores on average and those to the left lower performance scores. The regression value (y-axis) indicates the change in the mean of the genotype relative to others in line with the environmental capacity. Genotypes which are located on the regression line (value 1.0) demonstrate the average change in performance across environments, i.e. their performances respond in line with environmental capacity in a similar way to the average of all genotypes tested. Genotypes with a higher regression value (ie. higher on y-axis) are those that increase their relative performance in environments with a higher average value (i.e. more favourable), while genotypes further below the regression line are those that have higher relative performance in environments with a lower average value (i.e. less favourable).

4.1 Analysis of COPE dataset

COPE experiments were located at 12 locations (shown in Figure 3), and included a large number of accessions sown at each site in each year (Table 5). In this analysis, 'environments' were defined as site by sowing year combinations (i.e. site.sow year). The database may not have values when there was nothing to observe (i.e. a null measurement), so the record for biomass yield rating (BMY), for example could be a zero at a particular time. If the accession was sown at that site and other accessions were observed at that site for that year or observation then a value of 0 was allocated. This required records (for all traits) to be extracted for each site in order to look at which accessions had some records, which years had some records and then do an inner join to generate a "complete" set of records.

Table 5. Number of accessions sown at each COPE site each year.

Trial site	Abbrev.	1988	1989	1990
Brian Pastures Research Station		295	115	55
Brigalow Research Station	BrgRS	178	115	94
Calliope	Callp	282	65	100
Holyrood	Hlyrd	272	41	66
Mutdapilly		179	64	0
Silkwood	Slkwd	190	55	59
South Johnstone Research Station	StJRS	366	144	97
Southedge Research Station	SthRS	285	115	98
Tedlands (COPE)	Tdld	162	79	60
Willunga		278	54	2
Wolvi	Wolvi	274	58	102

4.1.1 Persistence to third year

The persistence of a species at a site has been defined for this analysis as the number of accessions with a non-zero biomass yield rating reported for the third season after sowing compared to the number sown. Please note that this does not indicate high productivity in year 3 but that the legume was present. The proportions for each species at each environment are presented graphically in Figure 4. The scarcity of data in the figure illustrates the complexity of the data set which has placed some restrictions on the statistical analysis. The large numbers of species planted in these trials would be better visualised using a different medium to allow zooming and interactive display. The variation in proportions of accessions that persisted for a given species is a combination of sampling variation, measurement variation and any genotype by environment interaction.

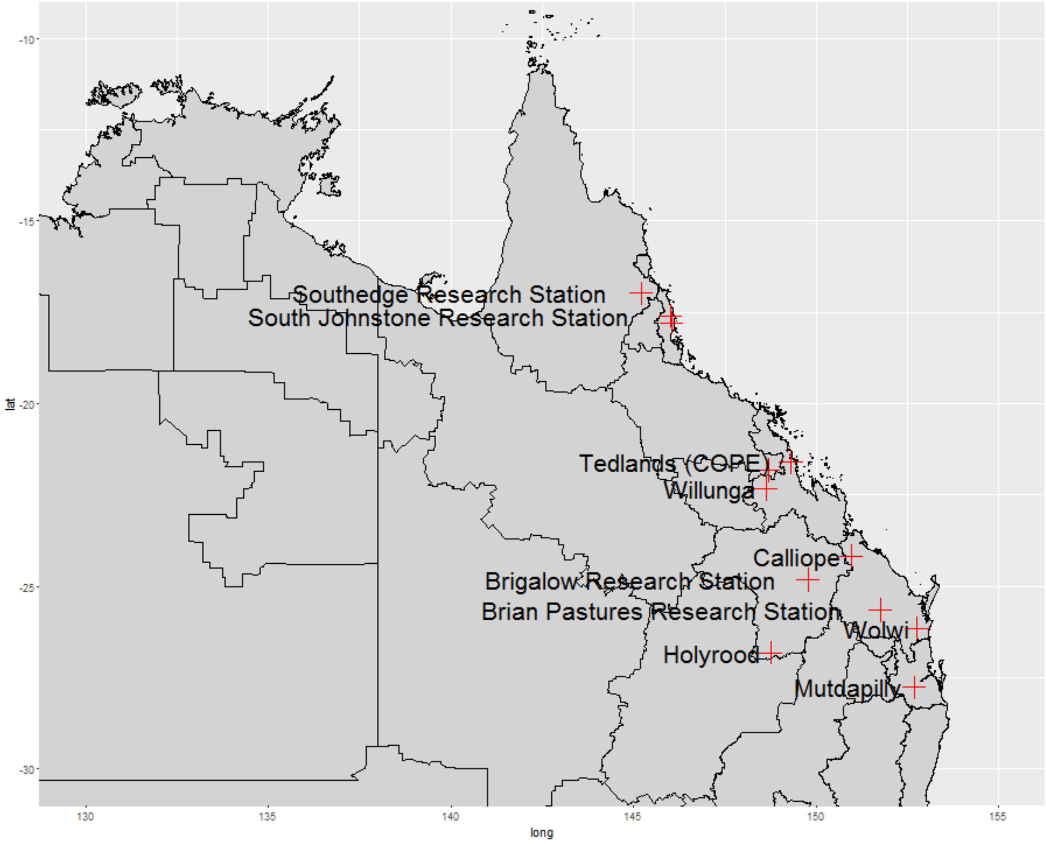

Figure 3. Map indicating the location of COPE trials.

The environments are ordered along the x-axis by increasing persistence in that environment; as are the species on the y-axis. The locations in the inland subtropics (e.g. Brigalow Research Station, Holyrood and Calliope sown in 1989 and 1990) had a lower persistence (<50% in all species) than the locations in the northern regions (e.g. South Johnson Research Station, Silkwood, Southedge Research Station) and environments with higher rainfall (e.g. Wolvi, Calliope 1988) (Fig. 4). There is also large variation amongst the species in their persistence at each location and no species persisted well at all locations where it was sown.

In the subtropical locations, the highest levels of persistence was observed in several *Desmanthus* and *Macroptilium* species at Holyrood and Calliope, and *Desmantus virgatus* at Brigalow research station. In the more tropical locations some species performed relatively well; *Arachis pintoi, Arachis glabrata, Chamaecrista rotundifolia, Aescheynomene brasiliana,* and *Aescheynomene americana.* In particular several of the *Rhynchosia* species had low persistence across most sites.

The Finlay-Wilkinson plot (Fig. 5) shows several *Desmanthus* species, *Vigna parkerii*, *Macroptilium lathyroides* and *Macroptilium longipedunculatum* persisted relatively well across environments. Several *Aeschynomene* species also persisted well but typically in the more favourable locations.

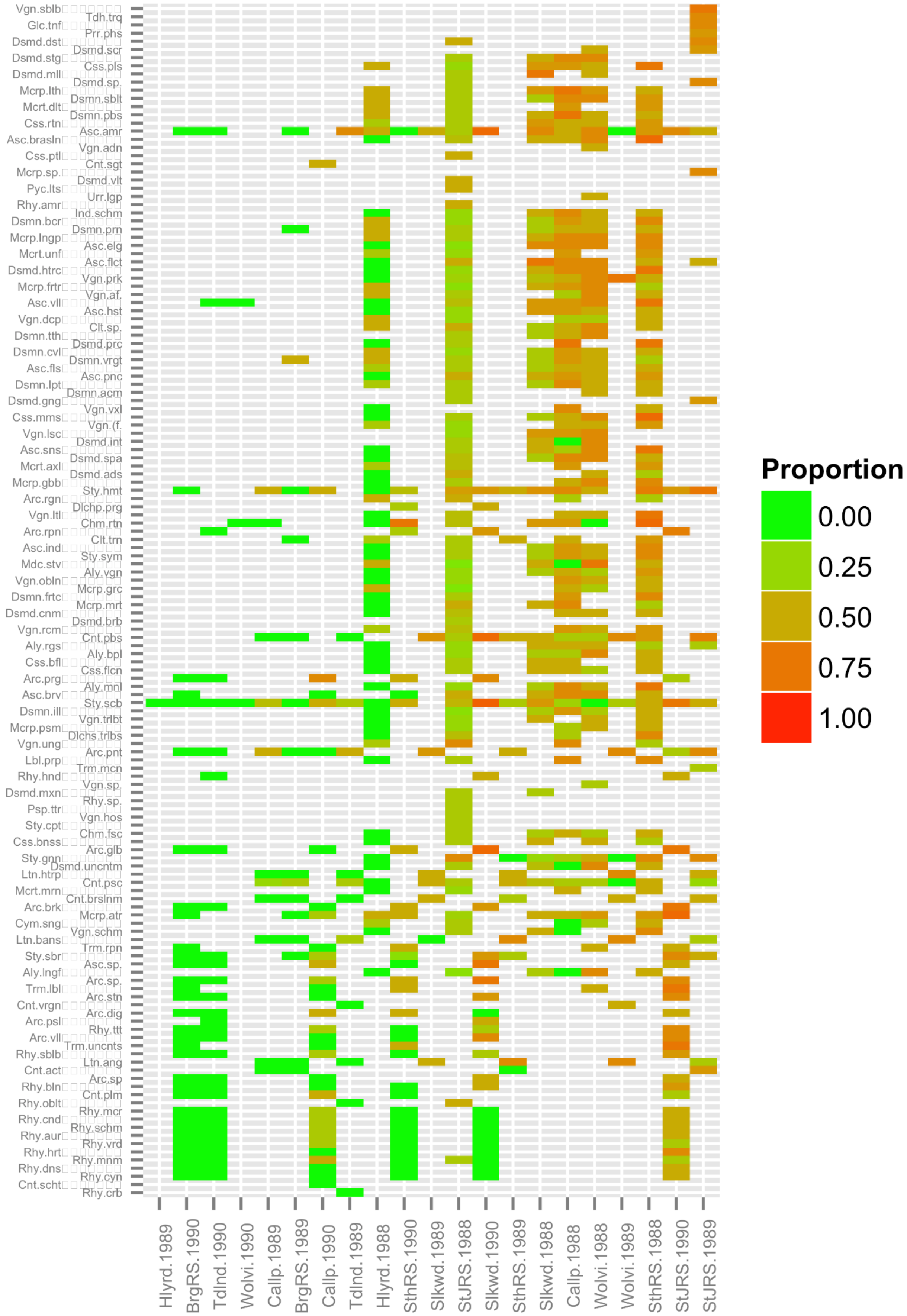

Figure 4. The proportion of successful COPE plantings of species persisting to year 3 across environments. Species (y-axis) are arranged from highest (top) to lowest (bottom) cross-site mean; Experimental site sowing year (x-axis) are arranged from lowest (left) mean to highest (right). The genus species label has been abbreviated, see Appendix B.

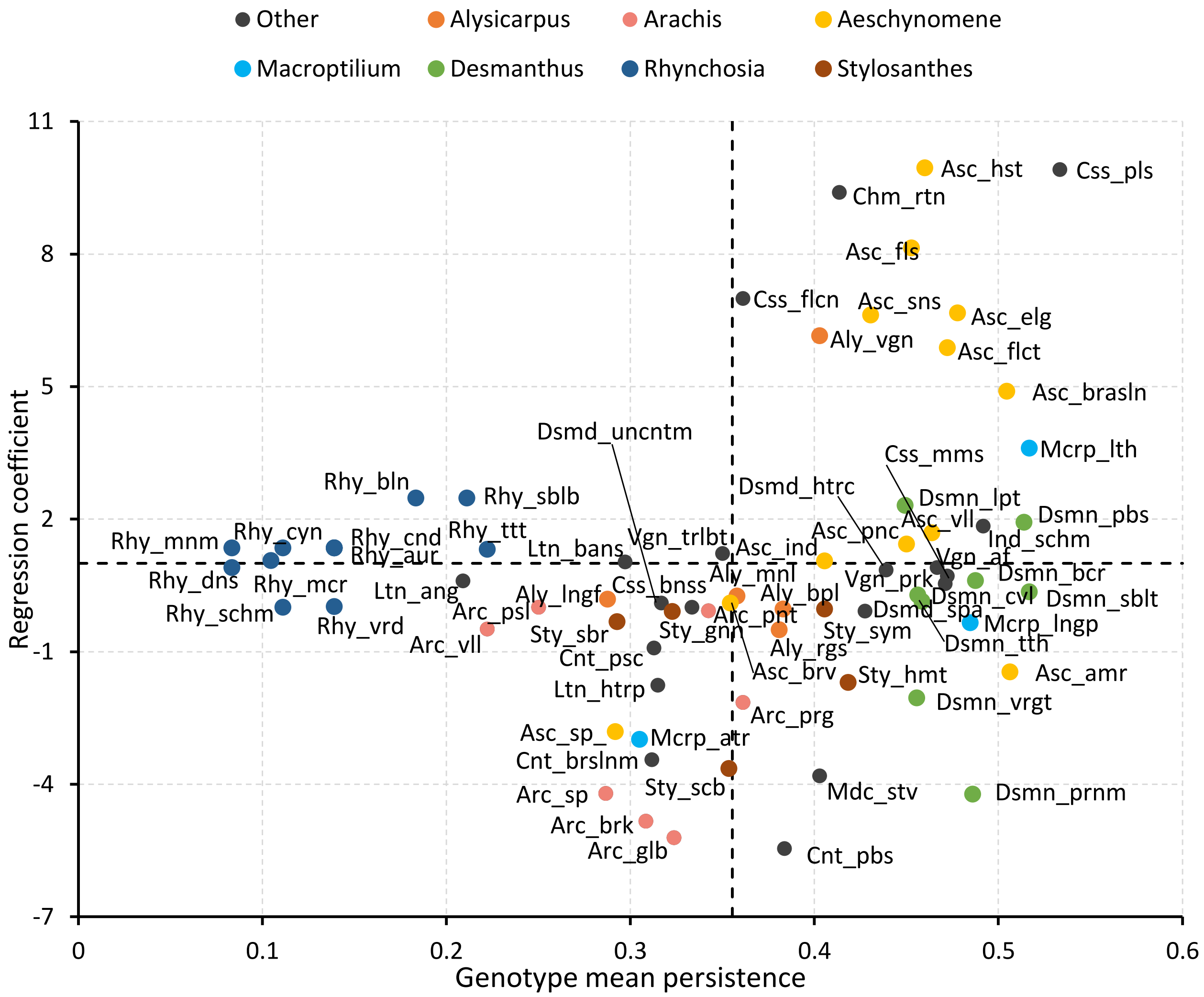

Figure 5. Finlay-Wilkinson plot for persistence to year 3 amongst species and environments in the COPE dataset. The species label has been abbreviated (see Appendix B); Species noted to the left are on average less persistent and to the right more persistent; Species indicated to the top perform are more responsive to more favourable environments and to the bottom perform better on average in less favourable environments.

4.1.2 Productivity in the first year

Biomass yield ratings in the first year of growth provide an indication of the quick establishment of a plant that would be desired by a producer. We analysed the biomass during the first season for many species using the Genotype X Environment Finlay and Wilkinson model like that used for persistence, as well as a factor analytic approach promoted by Smith et. al. (2014) for use in national crop variety testing programs. These models are considered superior to the variance component models approach which is the basis of the Finlay and Wilkinson analyses because they provide more accurate predictive values. Hence, this modified Finlay-Wilkinson analysis is the recommended approach for the meta-analysis here, however it does require specialist knowledge and software to process and interpret the output.

Several *Rhynchosia* and *Vigna* species (e.g. *V. oblongifolia, V. decipiens, V. hosei*) showed high production in year 1 but were highly location specific. Species with the highest year 1 production across multiple sites were *Macroptilium lathyroides, Macroptilium martii,* and *Centrosema pascuorum* (Fig. 6). The F-W plot for year 1 productivity (Figure 5) also showed *Macroptilium lathyroides* appears as a consistently high performer across many environments. The *Desmanthus* species had lower relative first year production but perform better in poorer environments.

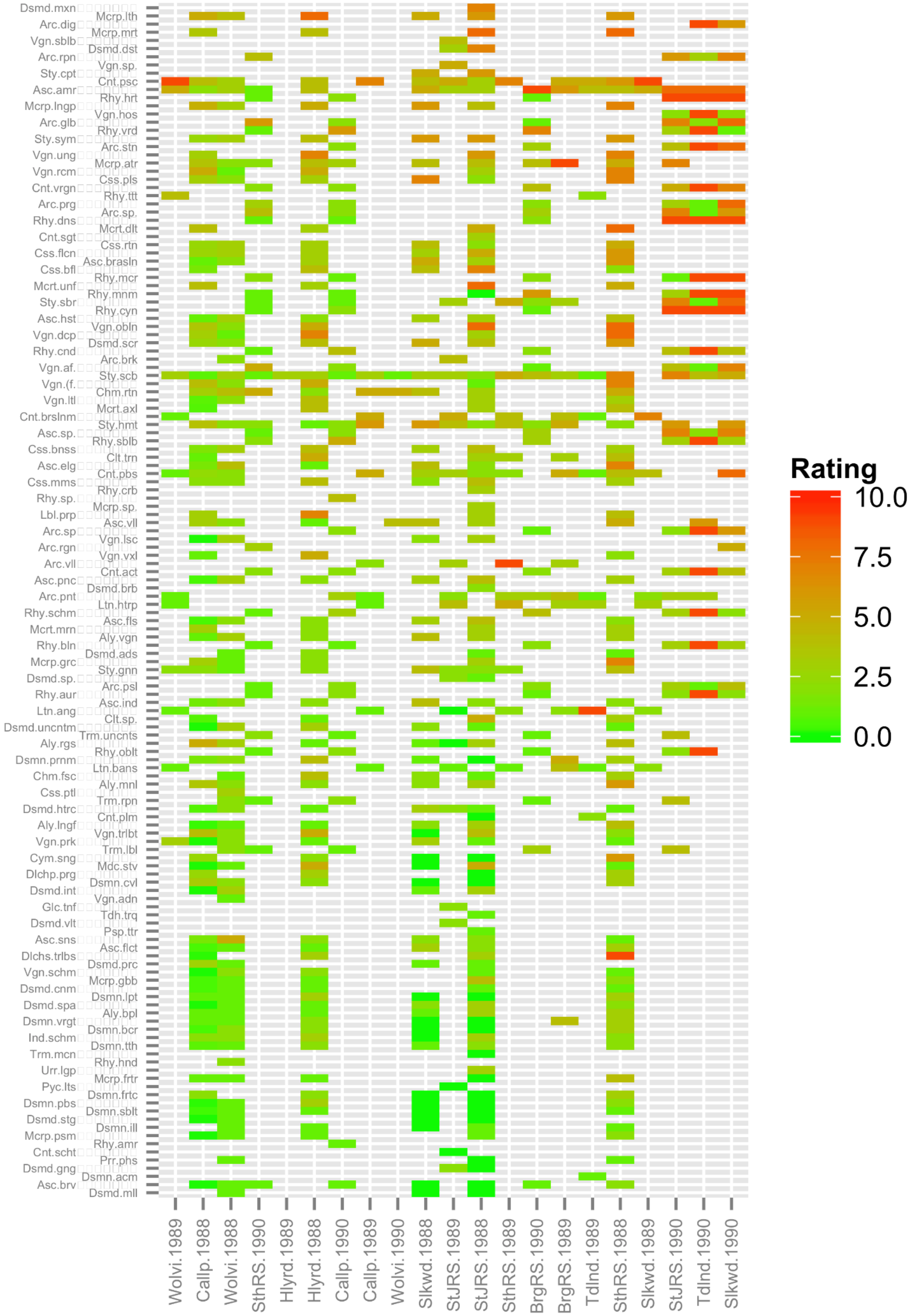

Figure 4. Average first year biomass yield ratings by species and environments from COPE dataset. Species (y-axis) are arranged from highest (top) to lowest (bottom) cross-site mean; Experimental site sowing year (x-axis) are arranged from lowest (left) mean to highest (right). The genus species label has been abbreviated, see Appendix B**.**

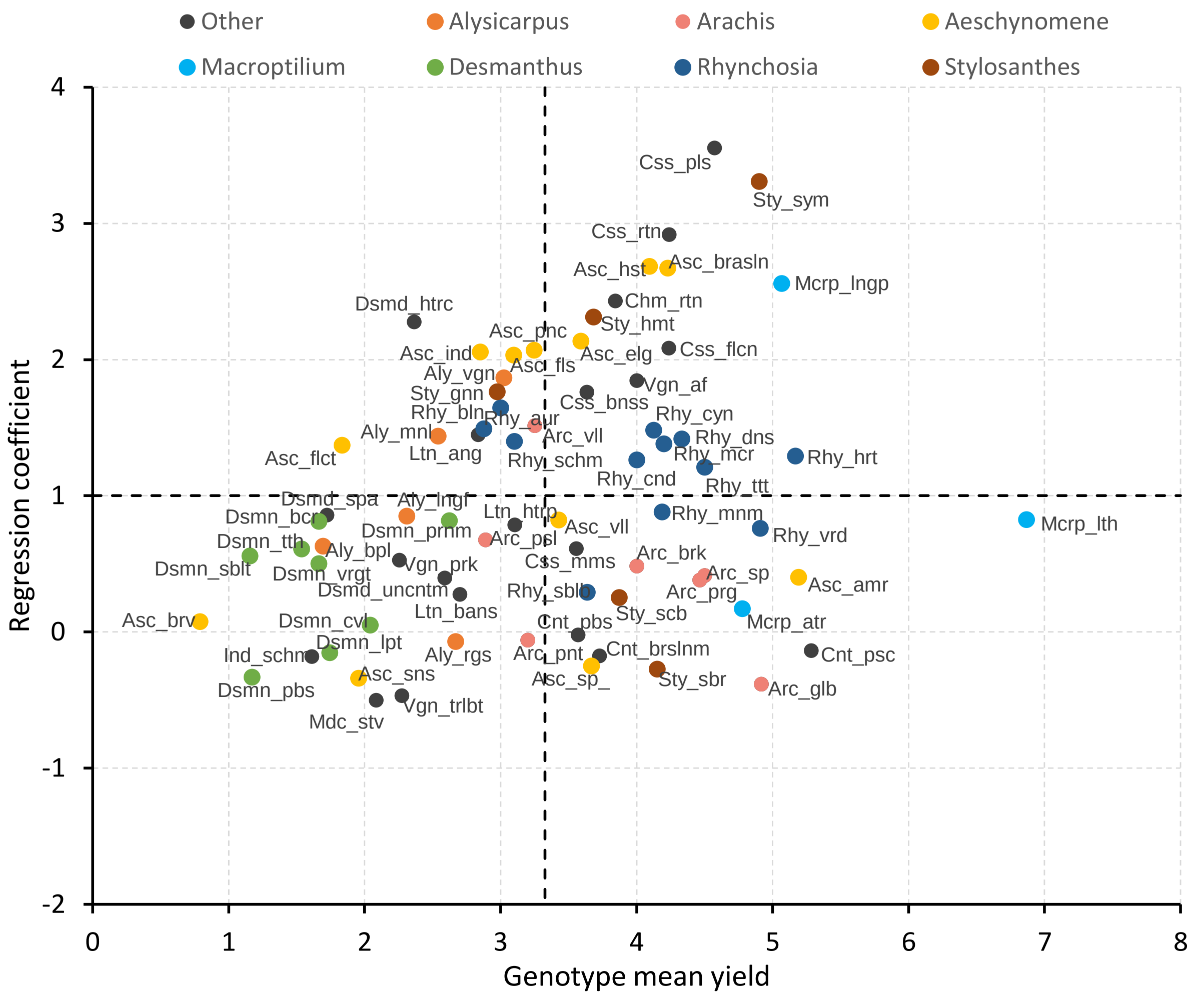

Figure 5. Finlay-Wilkinson plot for first year biomass production amongst species and environments in the COPE dataset. The species label has been abbreviated (see Appendix B); Species noted to the left are on average less productive in year 1 and to the right more productive in year 1; Species indicated to the top are more responsive to more favourable environments and to the bottom perform better on average in less favourable environments.

A four-factor analytical model was fitted to the year 1 productivity data to explain the Genotype X Environment interactions. The four factors explained 69, 17, 10 and 4 % respectively of the total G X E variance; i.e. 99% in total. The factors are related to environmental conditions across the various experimental years.sites, which are likely to be related to rainfall, temperature and soil conditions.

The top 20 performing species in terms of year 1 production at various environments predicted from this model are shown in Table 6. The standard errors of the predicted biomass rating vary according to their representation in the COPE data set. This score combines genetic and environmental effects to predict those species x environment combinations with the highest production in year 1.

The estimated between environment genetic correlation matrix from the factor analytic model is displayed graphically in Fig. 8. The rows and columns have been ordered on the basis of a dendogram as described in Smith 2015. Fig. 8 shows there is structure in the genetic correlations with one group of trials within which the pairwise correlation is high and positive. This group includes sowings at Calliope 1989, Willungra 1989, South Johnstone Research Station 1988 and 1989 and Silkwood 1988. The correlations amongst other experimental years are weaker or not present but in no cases was a negative correlation observed between sites.

Table 6. Top first year production ratings (0-10) amongst legume species evaluated in COPE across various environments.

Site.Year	Species	Predicted mean score	Standard error
Wolvi.1989	*Macroptilium lathyroides*	9.33	1.78
Tedld.1990	*Lotononis angolensis*	9.31	0.59
Tedld.1990	*Lablab purpureus*	8.76	0.78
Wolvi.1989	*Centrosema pascuorum*	8.71	0.43
Tedld.1990	*Medicago sativa*	8.68	1.12
SthRS.1989	*Alysicarpus rugosus*	8.57	1.05
Tedld.1990	*Rhynchosia verdcourtii*	8.50	0.90
Tedld.1990	*Rhynchosia aurea*	8.39	0.99
Tedld.1990	*Vigna trilobata*	8.37	0.83
Tedld.1990	*Indigofera schimperi*	8.33	0.83
Tedld.1990	*Rhynchosia oblatifoliata*	8.24	1.08
Tedld.1990	*Desmodium gangeticum*	8.20	1.33
SthRS.1988	*Macroptilium lathyroides*	8.19	0.59
Tedld.1990	*Desmanthus pubescens*	8.12	1.22
Tedld.1990	*Rhynchosia schimperi*	8.09	0.94
Tedld.1990	*Desmanthus leptophyllus*	8.00	0.70
SthRS.1989	*Desmodium adscendens*	7.99	2.11
Wolvi.1989	*Alysicarpus rugosus*	7.97	0.89
Slkwd.1990	*Chamaecrista rotundifolia*	7.96	0.67

Further analysis was also conducted to explore how some species of interest respond to changes in environment – this is indicated by a latent regression plot which helps to understand genotype stability and interactions with the four-factor genotype by environment interactions above (Fig. 9). We need to know how species of interest respond to changes in environment. The latent regression plots help to explore varietal stability.

The four factor loadings accounted for 69, 17, 10 and 4% together explained over 99% of the genotype by environment interaction. The first latent factor accounts for the maximum amount of variation (69%) in the predicted genetic effects. The first factor usually reflects the heterogeneity of genetic variance across the sites. Interpreting the factors is sometimes difficult but the loadings can be looked at to attempt to understand the importance of the sites. The loadings for the first factor are all positive so the factor is a general weighted average across sites with Wolvi in 1990 having the highest weighting. The second latent factor is a comparison of varietal performance across sites, Calliope in 1990, Brigalow in 1989 and 1990, Holyrood in 1988, Tedlands in 1990 compared to Calliope in 1989, Silkwood in 1990, Southwood in 1990 and South Johnstone in 1990.

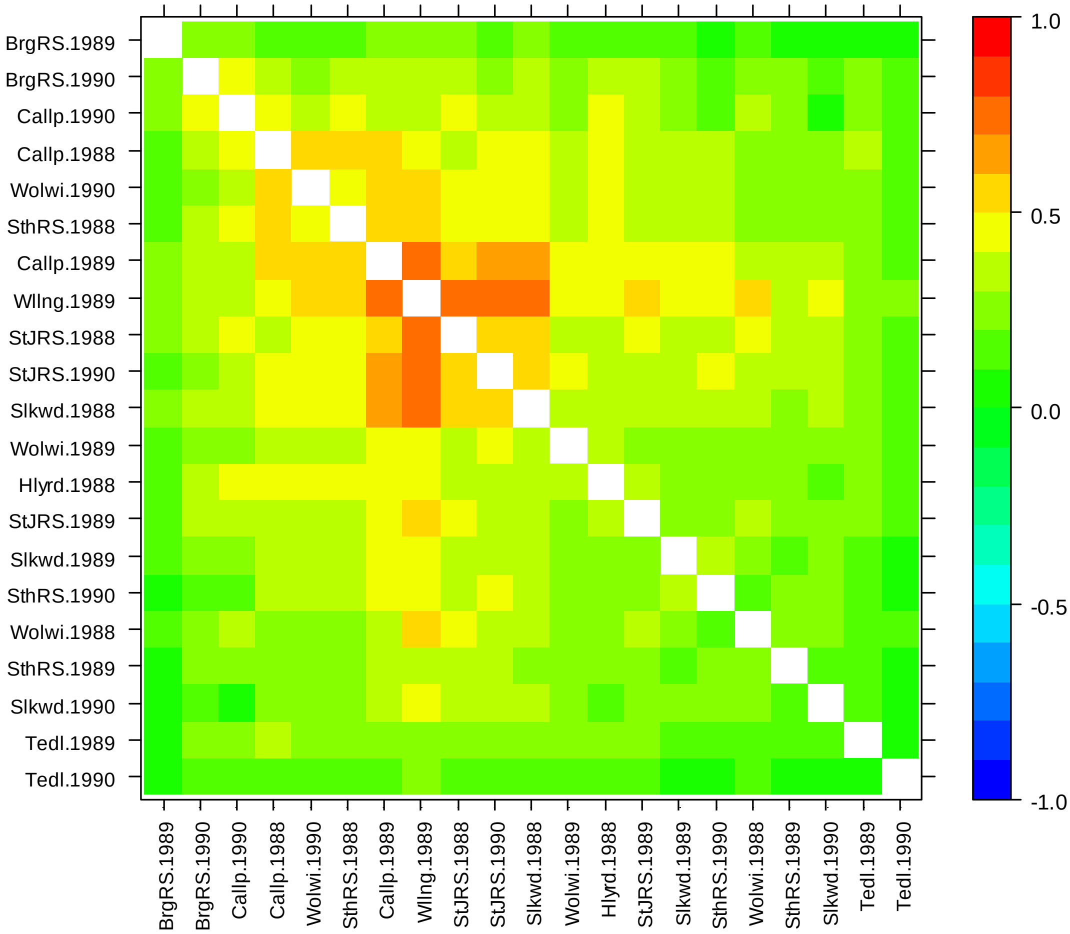

Figure 6. 'Heat-map' of the estimated genetic correlation matrix amongst evaluation environments in the COPE data, with environments (site.year) clustered by similarity. Each box is a pairwise comparison of species rankings between the two environments – if positively correlated (red) they have similar rankings amongst species, while if negatively correlated (blue) the ranking of species is reversed.

Figure 7 shows the regression plots for eight example species. Each factor is associated with attributes of the environment (it's not clear what they are, but probably related to rainfall and temperature), but the regression indicates the capacity of these species to either increase or decrease their ranking in response to these environmental attributes. The analysis in Fig 9 shows differences amongst species in their response to these environmental factors. For example, *Lotononis angolensis* performance values are nearly always negative and decrease for environments with high estimated loadings, while *Stylosanthes hamata* has the opposite response to these environmental factors. In response to factor 2, *Alysicarpus vaginalis* increases its relative performance significantly, while the performance of *Macroptilium lathyroides* and *Rhychosia verdcourtii* declines in response to these environmental factors.

The spread of points shown about the regression line also suggest the relative importance of each of the factors for a particular genotype. The interpretation of factors can be difficult, and further interpretation and analysis requires the use of environmental covariate information such as rainfall, temperature and soil type to fully understand differences in environmental factors.

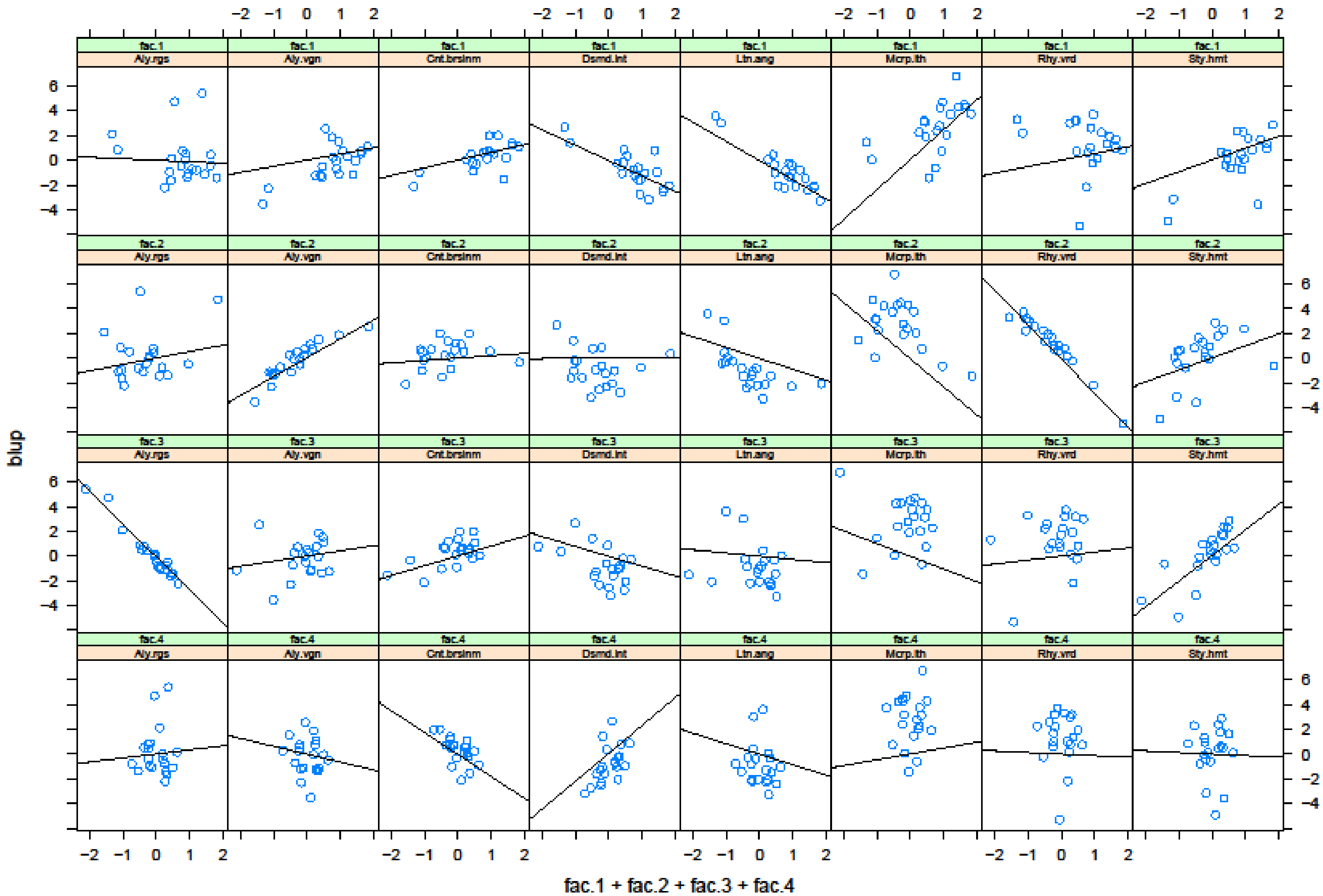

Figure 7. Latent regression plot for the first four environmental factors (arranged in rows) indicating there species respond quite differently to environmental factors. The solid line has a slope representing the predicted response of the genotype of these factors.

4.1.3 Productivity in the 3rd year

Analysis of productivity of legumes in their third year required some data manipulation so that if an accession was sown in year 1 and had no record for year 3, its yield was given as zero for year 3. Six hundred and fifty-seven ‘zero’ records were created to complete the year 3 biomass yield rating scores.

Figure 10 presents the species mean for third year biomass production across the full set of experimental site.years. The yield ratings were highest at the higher rainfall locations at South Johnston Research Station, Silkwood and Wolvi, where a large number of species had high yield ratings, though a few performed poorly. Meanwhile Brigalow Research Station, Holyrood and Tedlands had lower site means, though some species stood out at these sites, namely *Macroptilium atropurpureum*, *Macroptilium lathyroides*, *Clitoria ternatea* and several *Desmanthus* spp. at Holyrood and Calliope and *Stylosanthes scabra* at Tedlands and Calliope.

The Finlay-Wilkinson plot (Figure 1) suggests that several *Desmanthus* species and *Indigofera schimperi* had a high production in year 3 across a range of environments. A notable species here was *Mactoptilium* lathyroides which had a high mean yield in year 3 but also performed well in less favourable environments. *Chamaecrista (Cassia) rotundifolia* also performed better in less favourable environments, but had a lower mean yield than *M. lathyroides*. Several *Alysicarpus* species, *Desmanthus pubescens*, *Desmanthus subulatus* and *Stylosanthes sympodialis* showed higher year 3 production in more favourable environments.

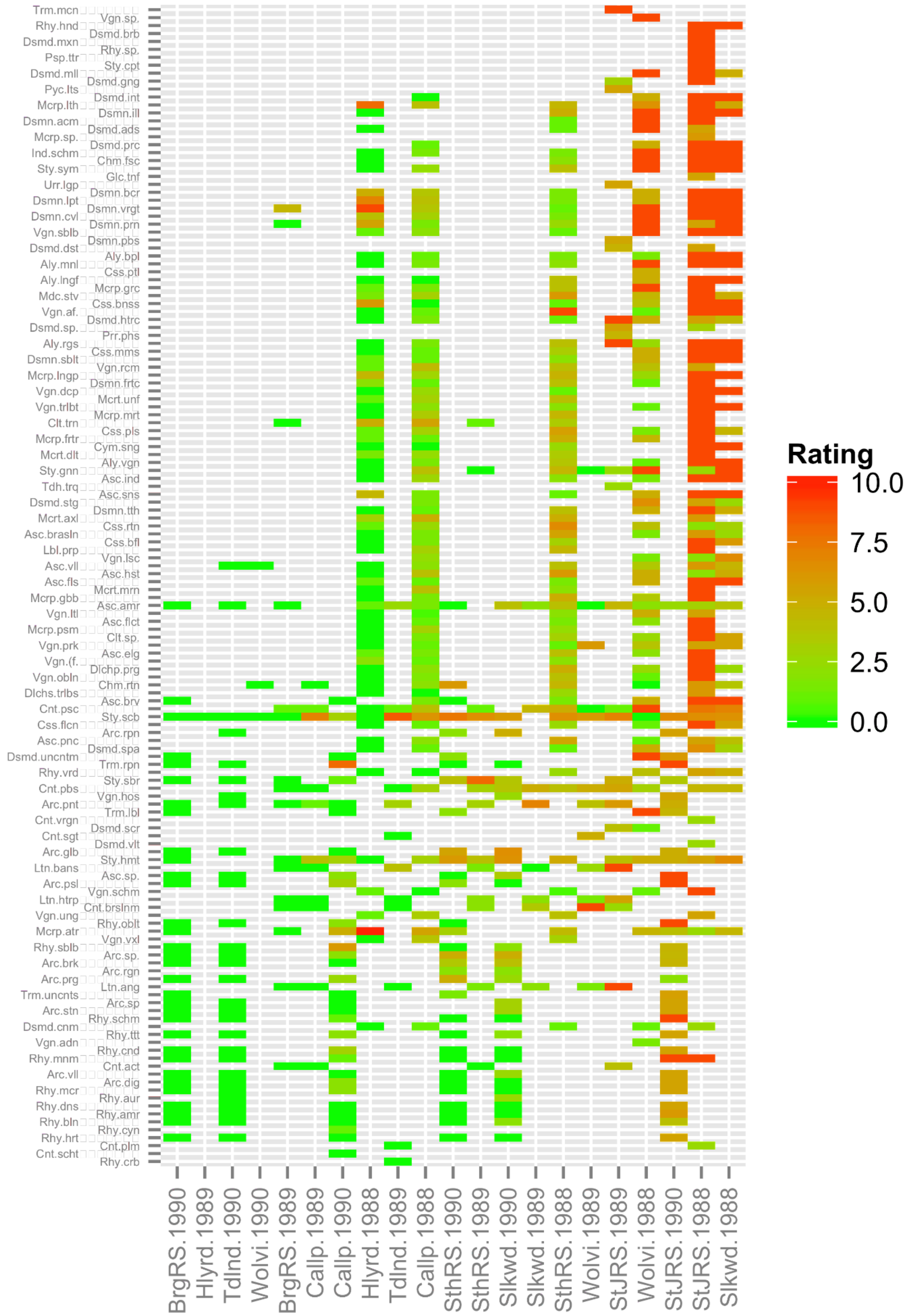

Figure 10. Average third year biomass yield ratings by species and environments from COPE dataset. Species (y-axis) are arranged from highest (top) to lowest (bottom) cross-site mean; Experimental site sowing year (x-axis) are arranged from lowest (left) mean to highest (right). The genus species label has been abbreviated, see Appendix B.

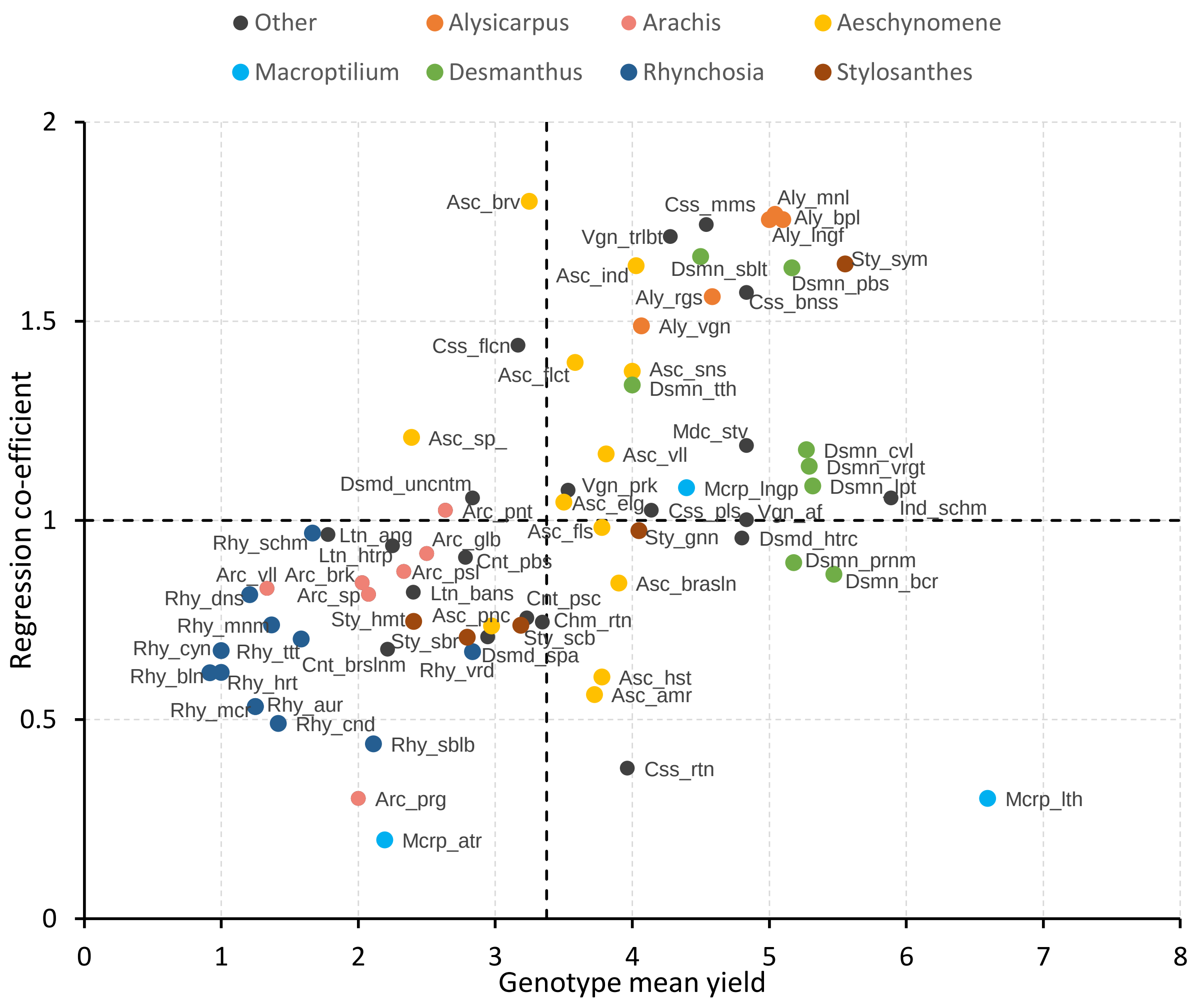

Figure 11. Finlay-Wilkinson plot for third year productivity amongst species and environments in COPE dataset. The genus species label has been abbreviated, see Appendix B; Species noted to the left are less productive in year 3 and to the right more productive in year 3 (dotted line indicates the mean of all species); Species indicated to the top perform better in more favourable conditions and to the bottom in less favourable conditions.

4.1.4 Growth between years 1 and 3.

To explore the dynamics of growth amongst the various legumes evaluated in COPE, changes in production scores between year 1 and 3 were calculated and subject to a G X E analysis.

The results in Figure 8 show the relative change in biomass scores between year 1 and 3 relative to other species; a positive value indicates an increase in ranking (i.e. increaser) and a negative value reduced their ranking between year 1 and year 3 (i.e. decreaser). This shows that several *Desmanthus* species showed a large increase in their productivity ranking from year 1 to year 3. Some did this reliably across all environments (e.g. *Desmanthus bicornutus)* while others did this where other species were also found to increase their productivity over time (indicated in the top right of Fig. 12). Several *Alysicarpus and Vigna trilabata* also significantly increased their mean yield from year 1 to year 3*.* *Rhynchosia* and *Arachis* species showed a large relative decline in productivity between year 1 and year 3.

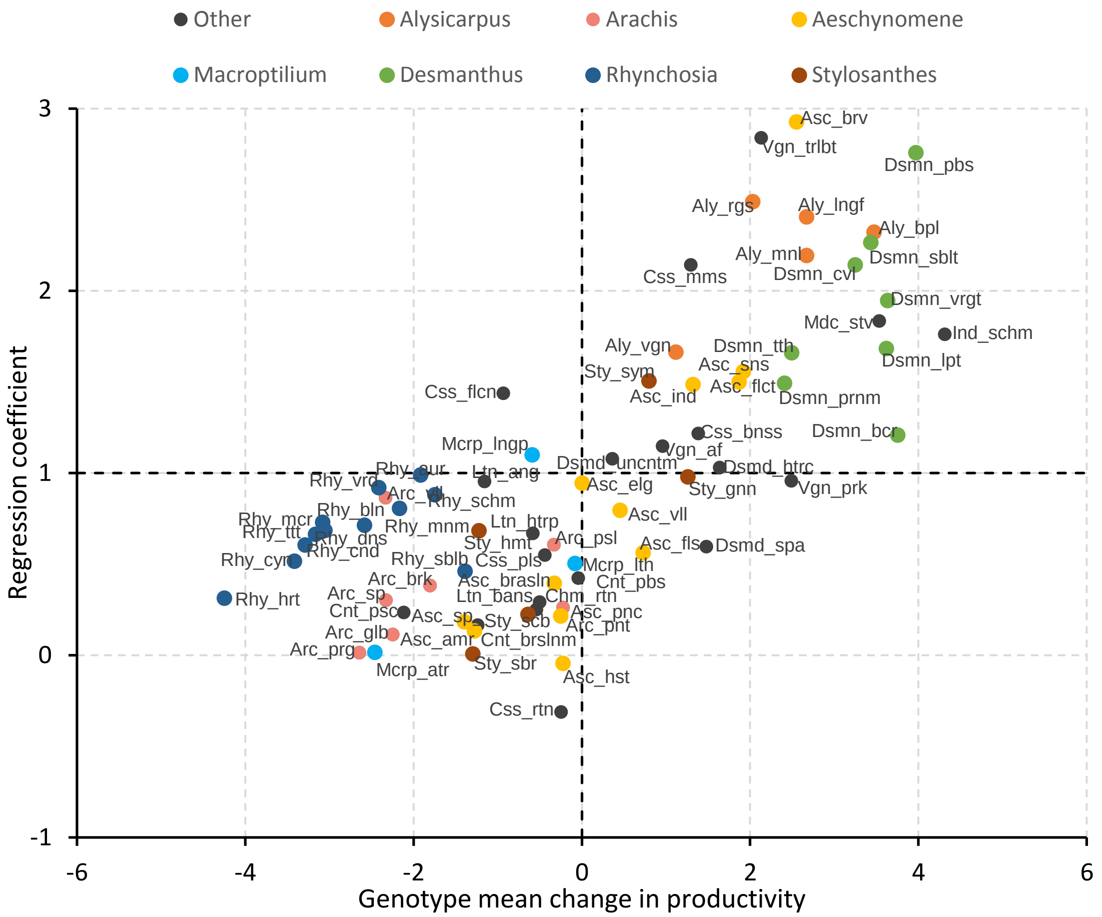

Figure 8. Finlay-Wilkinson plot for change in productivity rating between year 1 and year 3 amongst species and environments in COPE dataset. The genus species label has been abbreviated, see Appendix B; Species noted to the left (<0) reduced productivity rating and to the right (>0) increased productivity rating; Species indicated to the top increased under more favourable conditions and to the bottom in less favourable conditions.

4.2 Analysis of all tropical legume evaluations

The second analysis included all data where tropical legume species had been evaluated across a range of studies in northern Australia. The 52 sites at which a total of 41 tropical legume species were sown are shown in Figure 9. Biomass production observations were averaged over observed years for each site, since including year as a factor made the analysis too difficult to interpret and required a large amount of data manipulation. The trait used to measure productivity was not consistent across the different studies. Biomass yield rating (score 0-10) was measured on 67 occasions out of the 181 with the remaining 114 using biomass yield (kg/ha). To allow for a combined analysis, a Z-score was calculated by calculating the deviation from the site mean of all genotypes and scaled by the standard deviation calculated for each site. That is, a Z-score indicates the deviance of the genotype in standard deviations from the global mean of all genotypes for a particular site. If a Z-score is > 2 then that genotype performed in the top 5% and similarly a negative Z-score indicates that genotype performed in the bottom half of observations.

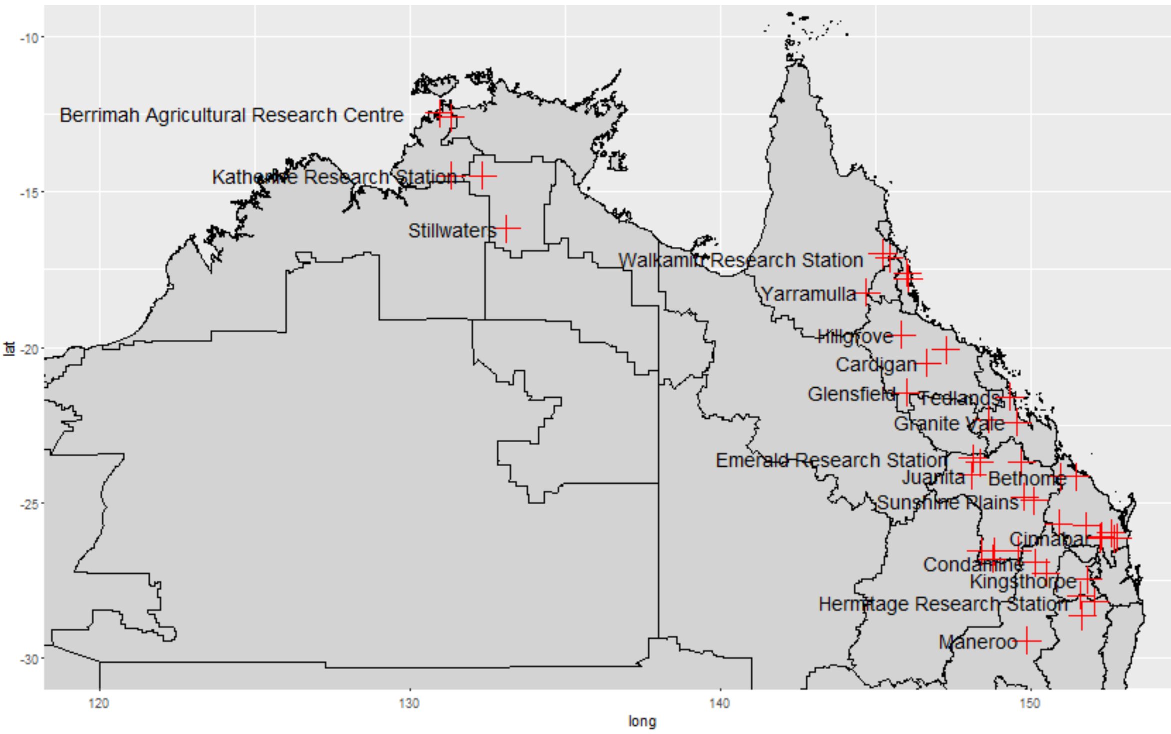

Figure 9. Locations of all evaluation sites included in overall analysis of tropical legume evaluation data.

Again, the species by site coverage is sparse and the data set was reduced to allow estimation of genotype by environment effects. Only sites with 10 or more accessions present and species with yield measures of 5 or more accessions were analysed, reducing the size of the dataset in the analysis. Species mean yield across all sites increases along the y-axis. This shows that *Stylosanthes scabra* had the highest mean yield across all sites, and was consistently better than average across sites but in particular had higher relative performance at some sites (e.g. Swans lagoon). Other species that ranked highly over many locations were *Aeschynomene brasiliana, Desmanthus pernambucanus, Macroptilium lathyroides* and *Chamaecrista rotundifolia* (Fig. 14).

However, the large regression coefficient values (absolute values) shown in the Finlay-Wilkinson plots (Figure 11) suggest further trimming of the data would provide more precise analysis. There was relatively little variation in z-score amongst species, on average all species fell within 0.6 standard deviations of the site mean. The Finlay-Wilkinson plot (Figure 11) indicates that *Aeschynomene brasiliana, Macroptilium lathyroides and M. atropurpureum* performed well in poorer environments while *Chamaecrista rotundifolia and Stylosanthes hamata* performed consistently across all environments.

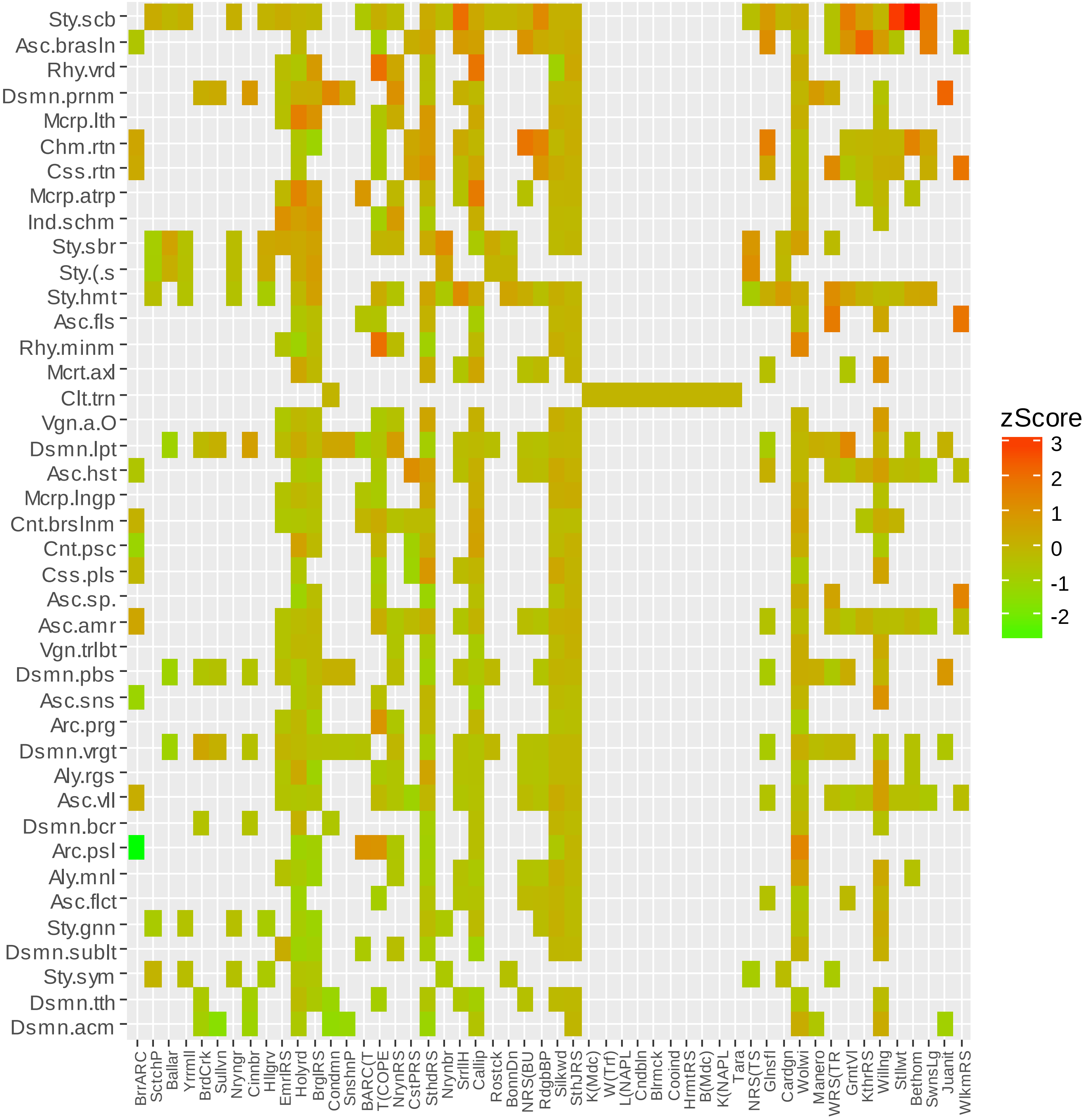

Figure 10. Species by site Z-scores for tropical legumes across 52 evaluation sites. Z-scores indicate performance of that genotype in standard deviations from the site mean. Sites are arranged from the least (left) to the most (right) records. Species (y-axis) are arranged from highest (top) to lowest (bottom) cross-site mean. The genus species label has been abbreviated, see Appendix B.

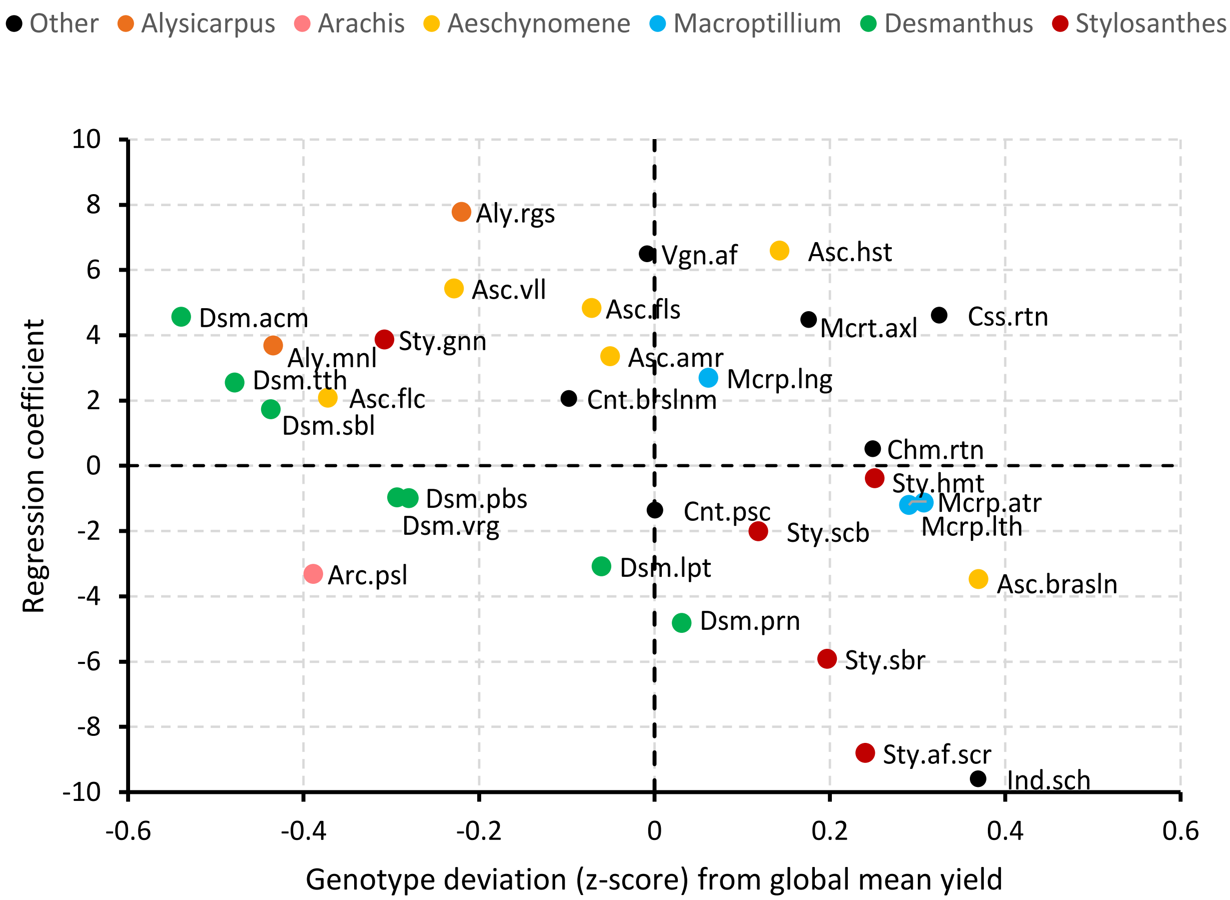

Figure 11. Finlay-Wilkinson plot of biomass z-score mean amongst species and environments in the dataset including all sites where tropical legumes were evaluated in northern Australia. The genus species label has been abbreviated, see Appendix B; Species noted to the left have lower average z-scores and to the right higher average z-scores; Species indicated to the top perform better in more favourable conditions and to the bottom in less favourable conditions.

4.3 Analysis of temperate legume evaluations

Yield data for 168 temperate species sown at a total of 67 sites was extracted from the database and the dataset was refined to include only sites with more than 10 accessions present (21 sites) and species with more than 5 accessions evaluated (see Figure 16). As for the tropical data, both yield ratings and biomass yield were used to measure productivity, necessitating the use of a standardising transformation to generate Z-scores. The average z-scores for yield for each species by site is shown in Figure 17. There were no candidates for consistent top performers at all environments across the temperate species.Similar to the analysis of the tropical species, the Finlay-Wilkinson plot (Figure 14) had relatively little variation in average z-score amongst species with all species within 0.45 standard deviations of the site mean. The analysis does demonstrate differences in the adaptation of species to more and less favourable environments. For example, *Medicago littoralis* and *Trifolium tumens* performing relatively better at sites with lower yields.

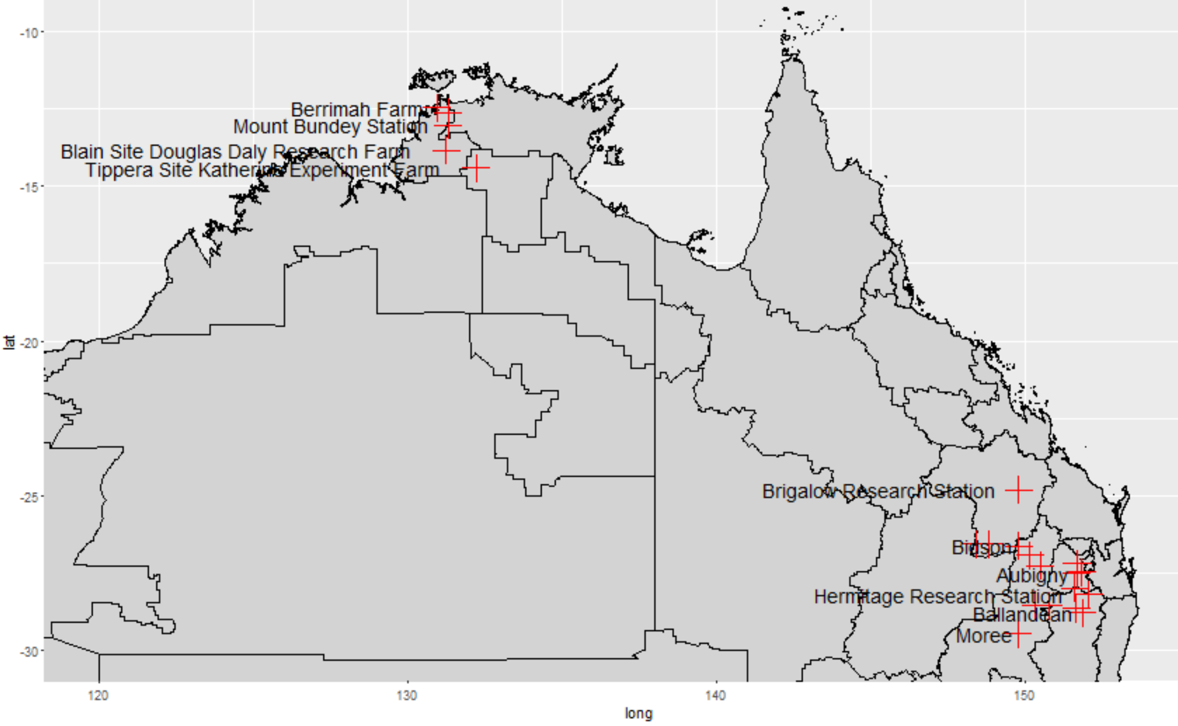

Figure 12. Locations of all evaluation sites included in overall analysis of temperate legume evaluation data.

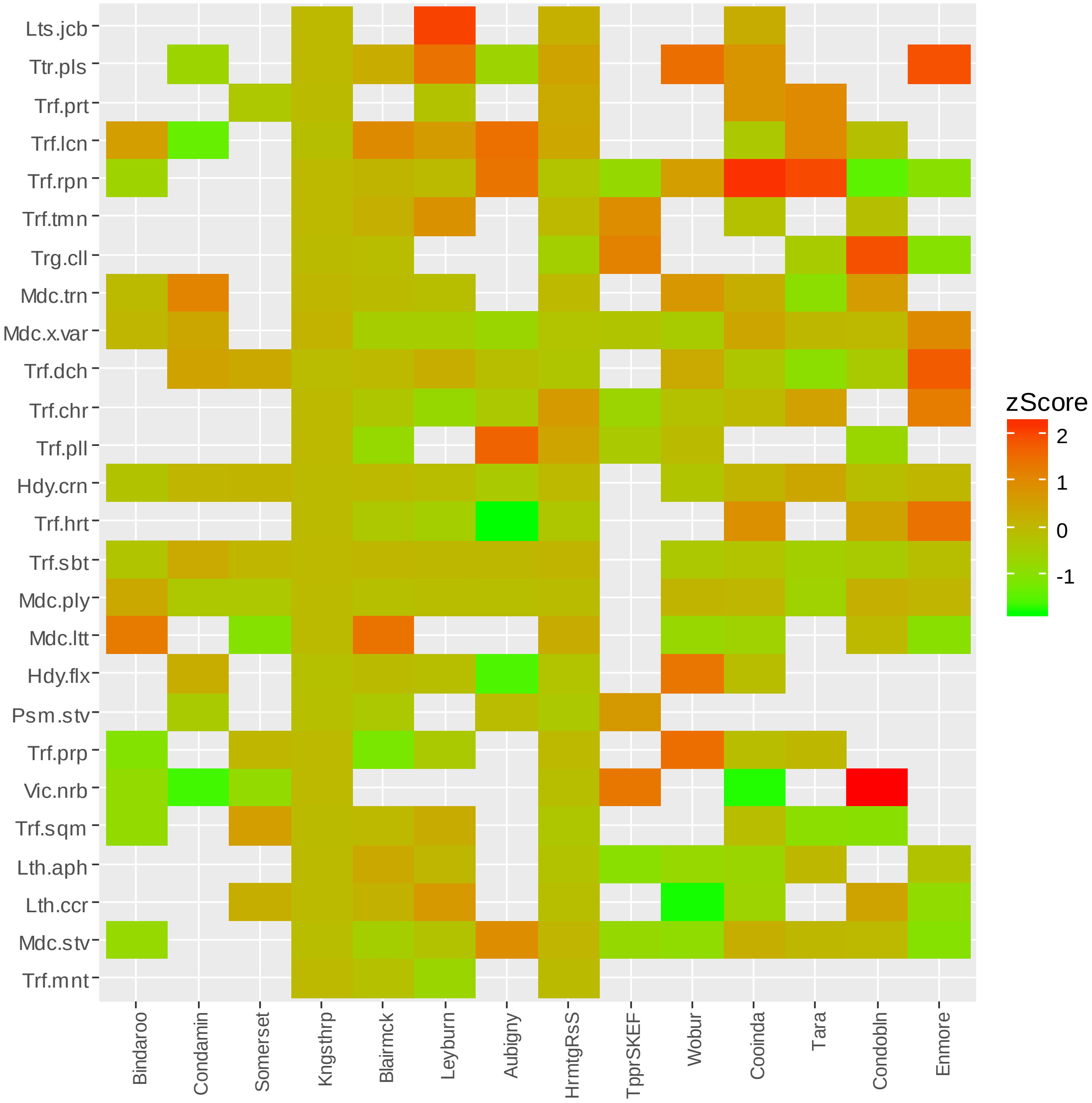

Figure 13. Average yield z-scores by species by site for temperate species. Z-scores indicate performance of that genotype in standard deviations from the site mean. Species are arranged from highest (top) to lowest (bottom) average Z-score across all sites. The genus species label has been abbreviated, see Appendix B.

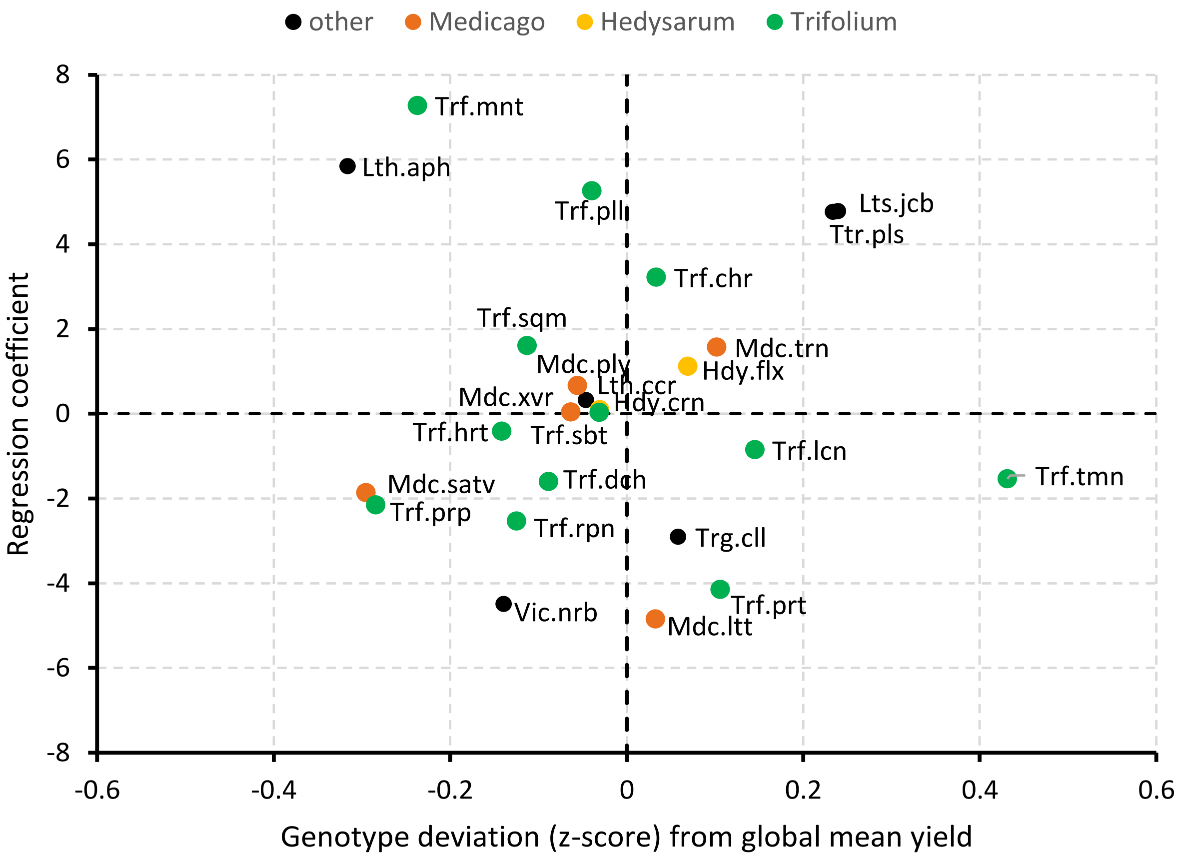

Figure 14. Finlay-Wilkinson plot of biomass z-score mean amongst species and environments in the dataset including all sites where temperate legumes were evaluated in northern Australia. The genus species label has been abbreviated, see Appendix B; Species noted to the left have lower average z-scores for forage yield and to the right higher average z-scores; Species indicated to the top of the figure perform better in more favourable conditions and to the bottom in less favourable conditions.

4.4 Conclusions from meta-analysis

The meta-analysis here across a range of evaluation locations and conditions has revealed several species that have higher productivity potential than commercially successful species and these may require some further investigation. In particular, several *Desmanthus* species showed high levels of persistence and higher year 3 productivity across a range of environments indicating they many have wider potential for development. Some *Macroptilium* species also demonstrated wide potential, with *Macroptilium lathyroides,* in particular, showing higher productivity levels in both year 1 and year 3 and performed relatively better than other species at locations with lower site yields. Some *Alysicarpus* species also were found to increase to have amongst the highest yields in year 3, particularly in more favourable conditions. However, some care should be taken with wider interpretation of this species performance analysis, as all accession for a species are included. Further examination of variation within species or comparisons amongst individual accessions may reveal further information on genotype performance across the full set of evaluation experiments here.

5 Legume gap analysis

The second component of the project involved a workshop to collate expert opinion on the following key questions:

- Which legume varieties are available by region (and broad land types within each region) and the extent to which regions/broad land types have an adequate range and number of proven cultivars.
- Any released varieties that have not been used much commercially despite performing well in trials and demonstrating adaptation in particular regions or land types.
- Priorities for future legume development for northern Australian pasture systems
  - Priority genera that were/are promising, but not well researched.
  - Priority species and lines within species that showed promise but were not released.
  - Highest priority regions/broad land types (climate by soil) for investment.
  - Highest priority genera and/or species for the priority regions/broad land types

A group of 17 pasture scientists including both current and retired staff from CSIRO, QDPI, NTDPI, NSWDPI and representatives from the three main pasture seed companies operating in northern Australia participated (the participant list is provided in Table 1) to provide a gap analysis on the current status of available legumes in the key beef production regions in northern Australia (Table 5).

5.1 Analysis of current options by region & land types

Australia's northern pasture area was broken up into 12 regions, which differ in their climatic and production systems and key land or soil types within each. These were:

- *Brigalow belt – south* – dominated by mixed farming involving cropping enterprises in the area south of Wandoan and the Great Dividing Range and east of Roma – St George and extending into northern NSW.
- *Brigalow belt – north* – dominated by mixed farming involving cropping enterprises in central Queensland north of Wandoan, excluding the spear-grass savannas.
- *South-west Qld*– region west of Roma and south of Tambo and extending into northern NSW
- *Central-west Qld* – Region west from Blackall to Cloncurry
- *North-west Qld* – Region north of Cloncurry and west of Richmond
- *North Qld – subcoastal* – Region north of Mackay and inland to Richmond including the Burdekin catchment but excluding the higher rainfall regions along the coast and tablelands
- *Coastal hinterland – south* – higher rainfall subtropical region along the coast east of the Great Dividing Range and south of Bundaberg
- *Coastal hinterland – north* – higher rainfall tropical region along the coast and hinterland to Townsville
- *North Qld and Wet tropics/coastal* – higher rainfall and tropical regions north of Townsville
- *North Qld – Tablelands* – Tablelands and higher altitude regions of northern Qld e.g. Atherton.
- *Northern Territory – top-end* – Northern part of the northern Territory.
- *Southern NT and northern WA* – southern part of the northern Territory, Pilbarra and Kimberley regions of WA.

Across these regions, a list of the currently commercially proven legumes which are currently used, adapted commercial options that are not widely used and prospective legumes was collated (Table

7) . Against each of these any limitations, constraints or risks to the wider use of commercial legumes and or development needs or advantages for prospective legumes are also documented.

This gap analysis reveals that several regions have very few, if any, adapted and commercially proven legume varieties available, some have a limited set of options that are well accepted, and other regions have several options that are known to be successful but have other constraints or limitations which limit their uptake or wider adoption. In most cases some possible avenues for development of legumes were identified.

5.1.1 Regions with few/no current legume options

South West and central western Qld, southern Northern Territory and northern Western Australia have virtually no legumes used. Some limited evaluation of legumes was conducted in the past in these areas but failed to identify any strong candidates for further development. Agro-climatic limitations along with economics of pasture augmentation in the low intensity production systems in these regions are also likely to limit the potential application of legumes in these regions.

Wider assessment of the potential of the commercially available *Stylosanthes* and current *Desmanthus* releases (e.g. Progardes, Marc) and possibly a wider range of *Desmanthus* species may be warranted in this region (particularly on the more fertile and productive clay soils e.g. Mitchell grass or Gidgee soils). The native legumes in the *Cullen* genus may also offer some potential here – some pre-commercialisation of *Cullen australasicum*, which is native in these regions has been initiated for low rainfall regions in southern Australia.

5.1.2 Regions with limited legume options

In much of the extensive and more arid regions of northern Qld (North-west and Subcoastal) and the top end of Northern Territory the only commercial options for use in mixed grass pastures are *Stylosanthes hamata* (Amiga or Verano stylo), *Stylosanthes scabra* (Seca or Siran stylo) and *Chamaecrista rotundifolia* (Wynn cassia). Their use is generally limited to lighter-textured soils, and there are few options for heavy clay soils. Other species identified that warrant further investigation to compliment these existing options on heavier clay soils include *Desmanthus* spp. and *Stylosanthes seabrana*, and on lighter textured soils *Centrosema brasilianum*, *Alysicarpus rugosus* and *Alysicarpus vaginalis*.

Several legumes are available and adapted for use as annual or shorter-term options on more productive areas in this region where cultivation is possible (e.g. *Centrosema pascuorum*, *Clitoria ternatea, Macroptilium* spp.). However, there is potential to expand their use through wider testing and promotion in these systems.

5.1.3 Regions with several adapted commercial options but adoption limited by key constraints

The higher rainfall coastal hinterland regions, wet tropics and northern tablelands have a much wider range of commercially proven legumes that fit a range of niches and production systems. However, several of these have specific zones of adaptation (sandy soils only, higher rainfall areas only) which limit the market size and hence seed availability (e.g. *Aeschynomene villosa*, *Lotononis* [now *Listia*] *bainesii* and fine stem stylo (*Stylosanthes guianensis* var. *intermedia*). Seed production is also a challenge for some prostrate grazing tolerant species suited in these areas, resulting in high seed cost or poor availability (e.g. *Arachis pintoi*, *Vigna parkeri*). Other freer seeding species are intolerant of heavy grazing in these intensive production systems (*Macroptilium atropurpureum* [Siratro], *Desmodium intortum* [Green-leaf desmodium], *Stylosanthes guianensis* var. *guianensis*). Wider use of *Leucaena* has been limited by psyllid damage, but may be increased with the release of the new hybrid cultivars. Several species known to be adapted in this region also pose some risks as environmental weeds (e.g. *Neonotonia wightii*, *Desmodium uncinatum*). Improvements in some of these attributes could widen the application of several of these species in these regions.

The brigalow belt, where mixed crop-livestock systems dominate, also possesses several adapted species, but widespread adoption of many is limited by agronomic or environmental constraints. The most widely used include annual medics (*Medicago* spp.), Lucerne and lablab in the south and leuceana, lablab and butterfly pea in the north of this region. In these areas there is much greater capacity to utilise annual or shorter-term legume options in association with cropping systems as well as to incorporate legumes with improved tropical grasses. However, in both these regions there are significant gaps in this array, particularly species suited to light or sandy soils. Several other commercial options are available with small areas of current adoption but wider application is limited primarily due to a lack of an agronomic package to accompany these species (e.g. *Stylosanthes seabrana*, *Desmanthus virgatus*, *Macroptilium bracteatum*).

Table 7. A gap analysis of current options and further opportunities/needs for pasture legume development in Australia's tropical pasture systems.
¥ Currently commercially proven legumes are those that are currently commonly used in the region, though they may still have limitations on their application and adoption; Ψ Commercial adapted options are those that have been released that are thought to be adapted in the region but are not commonly used or successfully adopted; Φ Other prospective species are those that are felt may have some application in the region but have not yet been widely tested or have restrictions to their further application; ‡Heavy soils have high clay content through the profile, Light soils have sandy or sandy-loam surfaces over a range of subsoil textures from sand to heavy clay.

Regions	Soil types‡	Currently commercially proven legumes ¥		Commercial, adapted options (not widely/successfully adopted) Ψ		Other prospective species or taxa Φ	
		Species (cultivar)	Risks/constraints	Species (cultivar)	Risks/constraints	Species/accession	Development needs/key attributes
Brigalow belt – Southern (Southward from Wandoan)	Heavy soils	*Macroptilium bracteatum* (burgundy bean)	• Not persistent in mixed grass pastures • Weak nodulator/N fixer • Establishment methods	*Stylosanthes seabrana* (Caatinga stylo - *cvv*. Unica, Prima)	• Seed supply chain • Variable seed quality & vigour • Specific root nodule bacteria (RNB) • Establishment reliability using current methods • Slow population buildup	*Desmanthus* spp. e.g. *D. tatuhyensis, D. pernambucanus*	• Highly productive & persistent, widely adapted • Low growing, grazing tolerant types • Heavy seeding & regeneration • Limited knowledge in this environment • Other promising accessions (Q9153)
		Lablab purpureus (lablab *cvv*. Highworth, Rongai)	• Seed production/forage trade-off (Rongai too late, Highworth too early) • Not suited to mixed grass pastures • Lack of perenniality (*cv*. Endurance not persistent,CPI24973 is highly persistent)	*Desmanthus leptophyllus* (*cv*. Bayamo)	• Poor persistence in drier and southern areas • *cv*. JCU1 (Progardes) still to be proven persistent	*Macroptilium* spp (e.g. *M. gracile*)	• Persistence with grass and under grazing • High N fixing *M. bracteatum*
		Leucaena spp.	• Frost tolerance • Productivity in shorter growing season • Mimosine toxicity	*Macroptillum atropurpureum* (*cv*. Aztec)	• Low grazing tolerance • Poor regeneration with grass competition under grazing	*Clitoria ternatea*	• Greater frost/cold tolerance?
		Desmanthus virgatus (*cv*. Marc)	• Seed supply chain • Establishment reliability using current methods • N fixation/nodulation • Slow population buildup	Sulla (*Hedysarum coronarium*)	• Short-lived, variable persistence • Disease susceptibility • High seed cost & variable seed supply • Not suited to mixed pastures (pure swards only)	*Macrotyloma daltonii*	• Heavy seeding annual (regenerating short-term pasture) • Palatability low or questionable • Susceptible to waterlogging
		Medicago spp. (annuals)	• Powdery mildew resistance • Reliance on southern seed supplies • Bloating risk	*Vigna unguiculata* (Cowpea)	• Less productive than lablab except on certain soils (e.g. sandy, acid soils) • Disease tolerance • Not suited to mixed grass pastures		
		Lucerne (*Medicago sativa*)	• Not persistent (short-term pasture) • Disease susceptibility issues • Adaptation (water efficiency) • Bloating risk	*Vicia villosa* (woolly pod vetch – *cvv*. Namoi, Haymaker)	• Too soft seeded to persist reliably • Toxicity concerns		
	Light soils	Nil		*Chamaecrista rotundifolia* (*cv*. Wynn cassia)	• Only on sandy-surfaced soils • Poor palatability • Variable persistence	*Stylosanthes scabra* (*cv*. Seca)	• Higher frost tolerance and persistence • Only for light soils
Brigalow belt –	Light			*Ornithopus compressus* (*cv*.	• Locally adapted (sandy soils only)	*Stylosanthes*	• Some lines have been sown to

Regions	**Soil types**[‡]	**Currently commercially proven legumes**[¥]		**Commercial, adapted options (not widely/successfully adopted)**[Ψ]		**Other prospective species or taxa**[Φ]	
		Species (cultivar)	Risks/constraints	Species (cultivar)	Risks/constraints	Species/accession	Development needs/key attributes
Southern con't	soils con't			Santorini)	• Variable seed availability in region (import from WA)	*seabrana*	perform well on light soils
				Biserulla & subclover	• Only locally adapted (wider range of soils, acid soils) • Variable seed availability in region (import from WA)	*Desmanthus* spp.	• Performance on light soils to be validated but anecdotal evidence of some adaptation
				Fine stem stylo (*Stylosanthes guianensis* var. *intermedia*)	• Narrow adaptation (sandy soils) • Seed supply chain		
				Lotononis bainesii	• Seed production challenges • High production variability (disease?)		
Brigalow belt – North (CQ) (Wandoan further north)	Heavy soils	*Macroptilium bracteatum* (burgundy bean)	• Not persistence in mixed grass pastures • Weak nodulator/N fixer • Establishment methods	*Stylosanthes seabrana* (Caatinga stylo - *cvv*. Unica, Prima)	• Seed supply chain • Variable seed quality & vigour • Specific RNB • Establishment method • Slow population buildup	*Vigna trilobata & Alysicarpus rugosus*	• Heavy seeding annual (regenerating short-term pasture) • For rotation legumes
		Lablab purpureus (lablab –*cvv*. Highworth, Rongai)	• Seed production/forage trade-off (*cv*. Rongai too late, *cv*. Highworth too early) • Not suited to mixed grass pastures • Perenniality (*cv*. Endurance not persistent, CPI24973 is highly persistent)	*Desmanthus leptophyllus* (*cv*. Bayamo)	• Poor persistence in drier and southern areas • JCU1 (Progardes) still to be proven persistent	*Macrotyloma daltonii*	• Heavy seeding annual (regenerating short-term pasture) • Palatability low or questionable • Susceptible to waterlogging
		Leucaena spp.	• Only on heavy soils • Establishment costs	*Macroptillum atropurpureum* (Aztec)	• Low grazing tolerance • Poor regeneration with grass competition under grazing	*Macroptilium* spp. (e.g. *M. gracile*)	• Persistence with grass and under grazing • High N fixing equivalent of *M. bracteatum*
		Desmanthus virgatus (cv. Marc)	• Seed supply chain • Establishment reliability • N fixation/nodulation • Slow population buildup • Risk of psyllids (to be confirmed)	*Centrosema pascuorum (cvv.* Cavalcade, Bundey*)*	• Hay production special purpose • Heavy seeding annual	*Desmanthus* spp. e.g. *D. tatuhyensis, D. pernambucanus*	• Highly productive & persistent, widely adapted • Low growing, grazing tolerant types • Heavy seeding & regeneration • Limited knowledge in this environment • Promising accessions (Q9153)
		Clitoria ternatea (*cv*. Milgarra)	• Only in certain grass mixes/soil types (not with buffel grass), otherwise in pure stands	*Vigna unguiculata* (Cowpea)	• Less productive than lablab except on certain soils (e.g. sandy, acid soils) • Disease tolerance • Not suited to mixed grass pastures	*Medicago orbicularis* (button medic) & *Medicago* spp.	• Very hard seeded • Only in wet winter seasons
Brigalow belt –	Light	*Stylosanthes*	• Establishment reliability	*Chaemachista*	• Only on sandy-surfaced soils	*Stylosanthes*	• Some lines have been sown to

Regions	Soil types‡	Currently commercially proven legumes ¥		Commercial, adapted options (not widely/successfully adopted) Ψ		Other prospective species or taxa Φ	
		Species (cultivar)	Risks/constraints	Species (cultivar)	Risks/constraints	Species/accession	Development needs/key attributes
North con't	soils	*scabra* (*cv*. Seca)		*rotundifolia* (*cv*. Wynn)	• Poor palatability	*seabrana*	perform well on light soils
		Stylosanthes hamata (*cv*. Amiga)	• Establishment reliability			*Desmanthus* spp.	• Performance on light soils to be validated but anecdotal evidence of some adaptation
South West, Qld (South-west Tambo-Roma)	Heavy soils	Nil		*Medicago* spp (annuals)	• Some early flowering varieties sown in some systems • Naturalised *M. polymorpha* in some areas	*Medicago laciniata* (cut leaf medic)	• Naturalised on red earths and clay soils in western NSW • Root nodule bacteria constraint to wider spread • Respond to late spring rains, highly seasonal
				Stylosanthes seabrana	• Some locations have persisted (mostly eastern edge of region), but performance still to be more widely proven	*Cullen spp.*	• Native legume, persistent and adapted in region.
						Desmanthus spp. *e.g. D. bicornutus, D. fruticosis*	• Still to be tested and persistence proven
	Light soils	Nil		Nil			
Central west, Qld (West of Blackall-Cloncurry)		*Stylosanthes scabra*	• Only on light soils	*Stylosanthes seabrana*	• Some locations have persisted (mostly eastern edge of region), but performance still to be widely proven	*Desmanthus* spp. e.g. *D. tatuhyensis, D. pernambucanus, D. bicornutus, D. fruticosis*	• Some examples of persisting material in region
				Desmanthus virgatus & D. leptophyllus (*cv*. Progardes)	• Still to be proven commercially	*Cullen spp.* (not Bullamon lucerne)	• Native legume, persistent and adapted in region. • Palatability and agronomic suitability?
North-west Queensland	Light textured soils	*Stylosanthes scabra* (*cvv*. Seca, Siran)	• Limited to 600+ mm	*Centrosema pascuorum* (*cvv*. Cavalcade and Bundey)	• Limited opportunity (farm): infrastructure/ rainfall	*Centrosema brasilianum* (*cv*. Oolloo)	• Appears well-adapted, but requires more testing.
		Stylosanthes hamata (cvv. Amiga, Verano*)*	• Biennial	*Clitoria ternatea (Milgarra)*	• Not promoted, testing required in the region	*Macroptilium bracteatum*	• Limited testing: establishes well and good wet-season growth
		Chaemaecrista rotundifolia (Wynn cassia)	• Limited to 800+ mm biennial • Weedy because of palatability concerns	*Macroptilium atropurpureum* (Aztec, Siratro)	• Don't persist under continuous grazing	*Stylosanthes macrocephala*	• Untested sprawling type: recommended to try as dry-season pasture legume (seed collectors)
					•	*Alysicarpus vaginalis* & *A. rugosus*	• Limited testing: naturalised in some areas. Useful germplasm?

Regions	Soil types[‡]	Currently commercially proven legumes[¥]		Commercial, adapted options (not widely/successfully adopted)[Ψ]		Other prospective species or taxa[Φ]	
		Species (cultivar)	Risks/constraints	Species (cultivar)	Risks/constraints	Species/accession	Development needs/key attributes
NW Qld con't	Grey clay soils	*Clitoria ternatea (cv. Milgarra)*	• Need to renovate to establish. Need good stock management. P Fertiliser	*Desmanthus virgatus* (*cv.* Progardes)	• Limited promotion/testing	Other *Desmanthus* spp.	• Potentially broad adaptation, unexplored germplasm
						Stylosanthes seabrana	• Yet to test fully
						Macroptilium bracteatum	• Early seeding types, should be well-adapted to soils
	Mitchell grass region	Nothing used	• Very low rainfall. Difficult to renovate Mitchell grass.			*Stylosanthes hamata* (diploid types)	• Potential for use on clay soils to provide legume protein in dry season
						Desmanthus spp.	• Potentially broad adaptation, unexplored germplasm
						Stylosanthes seabrana	• Yet to test fully
North Queensland - Subcoastal	Light textured	*Stylosanthes scabra* (*cvv*. Seca, Siran)	• Mod. Palatability, unreliable establishment			*Leucaena* hybrid (psyllid-resistant)	• Psyllid resistant dry-season fodder in dense grass pastures
		Stylosanthes hamata (cvv. Amiga, Verano*)*	• Biennial, unreliable establishment			*Alysicarpus vaginalis* & *Aly. rugosus*	• Limited testing: naturalised in some areas. Useful germplasm? Check Biloela work. Good seeders.
		Chaemaecrista rotundifolia (Wynn cassia)	• Mod palatability, biennial • Weed risk due to palatability concerns			*Centosema brasilianum* (*cv.* Oolloo)	• Limited testing: dry season pasture legume
						Clitoria ternatea	• Higher producing types?
						Macroptilium gracile	• Self-seeding dry-season pasture legume
						Stylosanthes macrocephala	• Untested sprawling type: recommended to try as dry-season pasture legume
	Heavy clay soils	*Clitoria ternatea (cv.* Milgarra*)*	• Drops leaf when dry, very palatable – requires management			*Desmantus virgatus*, *D. leptophyllus* and D. *bicornutus*	• Potentially broad adaptation, unexplored germplasm
						Stylosanthes seabrana	• Yet to test fully, dry-season pasture legume
						Stylosanthes hamata (diploid types)	• Potential for use on clay soils as a dry-season legume.
Coastal hinterland – south (Bundaberg south*)*		*Arachis pintoi*	• Seed supply (harvestability) is main constraint	*Aeschynomene americana* (*cvv.* Glenn, Lee)	• Too late flowering to set seed for regeneration - earlier flowering (56282) accessions available	*Alysicarpus rigosus*	• Weak perennials but high fixation and production

Regions	**Soil types[‡]**	**Currently commercially proven legumes [¥]**		**Commercial, adapted options (not widely/successfully adopted) [Ψ]**		**Other prospective species or taxa [Φ]**	
		Species (cultivar)	Risks/constraints	Species (cultivar)	Risks/constraints	Species/accession	Development needs/key attributes
		Chaemaecrista rotundifolia (Wynn cassia)	• Only on infertile sandy soils • Poor palatability and difficult to manage in mixed pasture • Later flowering varieties available that would reduce weediness	*Aeschynomene falcata* (*cv*. Bargoo)	• Highly persistent • Lack of seed supply due to harvest difficulties • Non-shattering varieties available that could improve seed production	*Macroptilium psammodes*	• CPI39098 – Persistent legume in humid and subhumid areas • Low seed production • Strongly stoloniferous
		Desmodium intortum (*cv*. Green-leaf)	• Intolerant of heavy grazing and hence poor persistence in intensive systems	*Macrotyloma axilaris*	• Seed production/supply challenges • Environmental weed risk	*Desmanthus virgatus*	• Q9153 – Higher production than Marc.
		Leuceana spp.	• Weed threat risk • Psyllid damage • Mimosine toxicity	Fine stem stylo (*Stylosanthes guianensis*) *cv*. Oxley	• Narrow adaptation (sandy soils) • Seed supply chain	*Arachis paraguariensis*	• High persistent • High quality, & spread into grass • Seed production (geocarpic)
		Lystia bainesii (lotononis)	• Seed production challenges • High variability in production (disease?*)*	*Aeschynomene villosa* (*cvv*. Reid, Kretschmer)	• Late flowering • Weak perennial, regeneration reliant on seed set	*Macrotyloma daltonii*	• Heavy seeding annual (regenerating short-term pasture) • Palatability low • Susceptible to waterlogging
		Macroptillum atropurpureum (*cv*. Aztec)	• Low grazing tolerance • Poor regeneration without disturbance	*Arachis glabarata*	• Vegetative propagation only		
		Medicago sativa	• Not persistent (short-term pasture) • Disease susceptibility issues • Adaptation (water efficiency) • Bloating risk	*Desmodium uncinatum* (*cv*. Silverleaf)	• Environmental weed		
		Neonotonia wightii (Glycine)	• Restricted to scrub soils • Environmental weed	*Macrotyloma uniforum*	• Regenerating annual • Only regenerates under certain conditions		
		Stylosanthes guianensis var. guianensis	• Anthracnose overcome with new cultivars (Nina, Temprano & others) • Variable persistence in mixed pastures	*Sesbania sesban* (*cv*. Mt Cotton)	• Poor palatability • Only locally adapted (restricted range)		
		Vigna parkeri (*cv*. Shaw)	• Only in humid coastal fringe • Limited seed supply & expensive	*Trifolium semipilosum* (*cv*. Safari)	• Poor persistence • Short-term productivity		
		Trifolium repens	• Only in humid areas and fertile soils with neutral pH • Not suited to acid soils	*Stylosanthes hamata* (*cv*. Amiga)	• Establishment reliability • Not promoted in the region		
Coastal hinterland – southern con't		*Lotus pedunculatus/ uliginosus* (*cv*. Maku)	• Best suited to acid soils • Lower production than white clover	*Stylosanthes seabrana*	• Not widely tested in region • Issues with establishment, seed supply, persistence with high grass competition		
		Stylosanthes	• Lower productivity than other	*Desmanthus*	• Earlier flowering cultivar to increase		

Regions	**Soil types**[‡]	**Currently commercially proven legumes** [¥]		**Commercial, adapted options (not widely/successfully adopted)** [Ψ]		**Other prospective species or taxa** [Φ]	
		Species (cultivar)	Risks/constraints	Species (cultivar)	Risks/constraints	Species/accession	Development needs/key attributes
		scabra (*cv*. Seca)	options in favourable areas	*leptophyllus* (*cv*. Bayamo)	seed set and regeneration (e.g. 38351)		
		Lablab purpureus (*cvv.* Highworth, Rongai*)*	• Seed production/forage trade-off (*cv*. Rongai too late, *cv*. Highworth too early) • Not suited to mixed grass pastures – cultivated areas	*Macroptilium bracteatum*	• Not persistence in mixed grass pastures • Weak nodulator/fixer • Establishment methods??		
Coastal hinterland – North (Bundaberg north)		*Stylosanthes hamata* (Verano, etc)	• Less adapted to wetter areas • High anthracnose risk in this environment	*Clitoria ternatea (cv.* Milgarra)	• Only on good/alluvial soils	*Macroptilium gracile*	• Grazing tolerance, prostrate • Back-up for *Aeschynomene americana* • Susceptible to Rhizoctonia
		Aeschynomene americana (*cvv*. Glenn, Lee)	• Powdery mildew and botrytis • Less adapted in drier areas	*Desmanthus virgatus & D. leptophyllus*	• No widely promoted • Seed availability • Smaller areas of heavier soils	*Desmanthus* spp. e.g. *D. tatuhyensis, D. pernambucanus*	• Highly productive, widely adapted • Low growing, grazing tolerant types • Palatable • Heavy seeding & regeneration • Long-lived • Limited knowledge in this environment • Other promising accessions (Q1593)
		Stylosanthes scabra (*cv*. Seca)	• Establishment reliability using current methods	*Aeschynomene villosa* (*cvv.* Reid, Kretschmer)	• Seed availability & supply chain problems		
		Chaemaecrista rotundifolia (Wynn Cassia)	• Only on infertile sandy soils • Poor palatability and difficult to manage in mixed pasture • Later flowering varieties available that would reduce weediness	*Stylosanthes seabrana*	• No widely promoted • Seed availability • Smaller areas of heavier soils		
		Leuceana spp.	• Weed threat risk is greatest • Psyllid damage major constaint • Mimosine toxicity	Fine stem stylo (*Stylosanthes guianensis* var. *intermedia*)	• Narrow adaptation (sandy soils) • Lower productivity than alternative stylo options • Seed supply chain		
		Stylosanthes guianensis var. *guianensis*	• Anthracnose overcome with new cultivars (Nina, Temprano & others) • Variable persistence in mixed pastures	*Centrosema pascuorum* (*cv*. Cavalcade)	• Not promoted/evaluated in the region • Limited to cultivated areas		
		Macroptillum atropurpureum	• Low grazing tolerance • Poor regeneration without disturbance				
North Qld, Wet tropics/ coastal		*Aeschynomene americana*	• Mildew, seed availability, annual habit	*Centrosema pubescens* (*cv.* Belalto)	• Limited demand, small market	*Desmanthus* spp.	• Potentially broad adaptation, unexplored germplasm
		Centosema molle (*cv*. Cardillo)	• Poor seeder 1st year, establishment into grass	*Macroptillum atropurpureum* (*cvv.* Aztec, Siratro)	• Poor persistence under set stocking	*Macroptilium bracteatum*	• Crop/graze or ley farming system? Moderate regrowth, clay/loam soils
		Stylosanthes	• Easily grazed out, good for hay,	*Lystia bainesii*	• Difficult seed production, small market	*Leucaena* hybrid	• Psyllid resistant dry-season fodder

Regions	**Soil types**[‡]	**Currently commercially proven legumes** [¥]		**Commercial, adapted options (not widely/successfully adopted)** [Ψ]		**Other prospective species or taxa** [Φ]	
		Species (cultivar)	Risks/constraints	Species (cultivar)	Risks/constraints	Species/accession	Development needs/key attributes
		guianensis var. *guianensis* (ATF3308, ATF3309)	establishment into grass using current methods	(Lotononis *cv*. Miles)		(psyllid-resistant)	in dense grass pastures
		Chaemaecrista rotundifolia (Wynn Cassia)	• Biennial, low palatability (limited role – sandy, overgrazed)	*Arachis pintoi* (*cvv*. Amarillo, Bolton)	• Seed production is major problem and results in very high seed price	*Centrosema pascuorum* (hay)	• Legume hay/ green manure?
		Lablab purpureus (*cv*. Highworth)	• Annual, fodder bank or green manure crop only	*Calopogonium mucunoides*	• Low palatability, no seed, naturalised	*Stylosanthes capitata*	• Acid soils (grew well at Walkamin)
		Vigna unguiculata (cowpea *cv*. Ebony)	• Annual, fodder bank or green manure crop only				
		Glycine max	• Annual, fodder bank or green manure crop only				
North Qld - Tablelands		*Vigna parkerii* (*cv*. Shaw)	• Seed price is high due to seed production difficulties. Establishment unreliable into existing grass pastures	*Aeschynomene villosa* (*cvv*. Reid, Kretschmer)	• Small market, no seed production • Moderate grazing tolerance	*Arachis pintoi* (ATF2320, ATF494, CPI1006)	• High biomass pasture and hay IF seed production ok / vegetative – digger / planter
		Neonotonia wightii (*cv*. Tinaroo)	• Less vigorous than Malawi, establishing in grass pastures	*Neonotonia wightii* (Malawi)	• Seed supply & small market	*Arachis glabrata* (Prine, CPI93469, CPI93481)	• Seed production is major problem and results in very high seed price
		Desmodium intortum (*cv*. Green-leaf)	• Intolerant of heavy grazing and hence poor persistence in intensive systems	*Arachis pintoi* (cvv. Amarillo, Bolton)	• Seed production is major problem and results in very high seed price	*Vigna parkeri*	• High seed production and ability to grow in dense grass pastures (e.g. *Brachicaria*)
		Centosema molle (*cv*. Cardillo)	• Poor year 1 seed production, difficult establishment in grass pastures	*Desmodium uncinatum* (*cv*. Silverleaf)	• Limited market, no seed production, environmental weed.	*Centosema molle*	• Better seed production to allow persistence in in dense grass pastures (e.g. *Brachicaria*)
		Stylosanthes guianensis var. *guianensis*	• Good disease tolerance • Poor grazing tolerance	*Macroptyloma axillare* (*cv*. Archer)	• Palatability and moderate grazing tolerance • Low seed production	*Leucaena* hybrid (psyllid-resistant)	• Psyllid resistant dry-season fodder in dense grass pastures
		Centrosema pascuorum (*cv*. Cavalcade)	• Annual. Fodder bank or hay production only.	*Trifolium semipilosum* (*cv*. Safari)	• Naturalised, no market	Temperate options – e.g. *Trifolium, Medicago* spp.	• Winter-active legumes to complement tropical grasses
Northern Territory – Top end		*Stylosanthes scabra* (*cvv*. Seca, Siran)	• Mod. Palatability	*Centosema brazilianum* (Oolloo)	• Limited interest	*Chamaecrista pilosa*	• Grew well and persisted in wetter area. Role in system is unclear
		Stylosanthes hamata (*cvv*. Amiga, Verano)	• Biennial	Macroptilium gracile (Maldonado)	• Limited interest	*Stylosanthes guianensis* (ATF3308, ATF3309)	• Potential role for hay production.
		Chaemaecrista rotundifolia (Wynn	• Mod palatability, biennial • Weed risk	*Centrosema pascuorum*	• Late flowering • Limited market competing with	*Leucaena* hybrid (psyllid-resistant)	• Dry-season fodder in dense grass pastures on heavy soils types

Regions	**Soil types[‡]**	**Currently commercially proven legumes [¥]**		**Commercial, adapted options (not widely/successfully adopted) [Ψ]**		**Other prospective species or taxa [Φ]**	
		Species (cultivar)	Risks/constraints	Species (cultivar)	Risks/constraints	Species/accession	Development needs/key attributes
		Cassia)		(Bundey)	Cavalcade		
		Centrosema pascuorum	• *Rhizoctonia* (repeat cropping), fodder bank or hay crop only	*Calopogonium mucunoides*	• Low palatability, no seed, naturalised	*Desmanthus* spp.	• Potentially broad adaptation, unexplored germplasm
		Lablab purpureus (*cvv*. Highworth, Rongai)	• Annual, fodder bank only	*Alysicarpus vaginalis*	• Naturalised, annual • Needs P to be productive and persistent.		
		Vigna unguiculata (cowpea *cv*. Ebony)	• Annual, fodder bank or green manure crop only				
		Clitoria ternatea (cv. Milgarra)	• Drops leaf when dry, very palatable – requires management, only on fertile clay soils				
Southern Northern Territory and Western Australia		Nil				*Stylosanthes hamata*	• Appears best option to try as regenerating pasture legume

5.2 Priorities for future legume development for tropical pasture systems

Based on the analysis of current legume options available for pasture systems in northern Australia, below we provide some assessment of where there is likely to be greatest prospect from further evaluation and development of legumes for tropical pasture systems.

5.2.1 Priority genera that were promising, but not well researched.

The genus *Desmanthus* is seen to offer the greatest potential for more detailed research in northern Australia. Meta-analysis conducted here revealed several *Desmanthus* species have high relative productivity and this is confirmed with expert opinion that there is greater potential in this genus. While some cultivars have been released, previous and small ongoing evaluation work (privately funded) on the genus has found several other accessions and species with promise of wider adaptation including sub-humid and arid regions and on lighter textured, acidic or saline soils. Greater understanding of rhizobiology and agronomic attributes of *Desmanthus* would also enhance the capacity to develop more commercial species in this genus.

A large coordinated evaluation of *Stylosanthes* has been undertaken across northern Australia and it is unlikely any further species will be uncovered, which would greatly expand the repertoire of commercial species in this genus. Some species are used elsewhere in the world but not used in Australia (e.g. *S. capitata*) might be worth examining in targeted environments (e.g. acid soils) and more systematic exploration of *Stylosanthes* for higher frost tolerance could help expand their zone of adaptation (e.g. *Stylosanthes seabrana*). There may also be significant prospects to make use of *in situ* selection of existing species for better adaptation across the wide range of climates and soil types (*Stylosanthes* spp. and *Desmanthus virgatus*). That is, collect and evaluate material where sown legumes have persisted and probably undergone selection for those genotypes that are best adapted to conditions in those soils or areas.

5.2.2 Promising lines or variation within species not yet released

A number of promising species and accessions were identified that could offer prospects for improved productivity, to fill gaps in the current array of options or widen the adaptation of particular successful legumes in northern Australia. This list is likely to include those that could be easily progressed in further evaluation activities to compare against existing material and/or across a wider range of environments to validate their further potential.

- *Desmanthus virgatus Q9153* – higher production and higher seedling regeneration than *cv*. Marc
- *Desmanthus leptophyllus* AC10 & AC11, TQ90– earlier flowering than *cv*. Bayamo, and hence wider adaptation particularly in lower rainfall areas (<600 mm)
- *Aeschynomene falcata* ATF2194, ATF2196 – better pod holding, less shattering (overcome seed harvest issues) than *cv*. Bargoo
- *Aeschynomene americana* CPI 56282– earlier flowering than *cv*. Glenn or *cv*. Lee which may enable the range of the species to be extended south and into drier areas.
- *Stylosanthes seabrana* – some lines are thought to be more promiscuous in their root nodule bacteria requirements than *cvv*. Unica and Primar, which would reduce the need for specific root nodule bacteria inoculation and other perceived limitations in nodulation and N fixation. However, the taxonomy of these accessions is unclear as their morphologically dissimilar to other *S. seabrana* (Date 2010). Early evaluation for

frost tolerance identified more tolerant lines but the commercial lines were not evaluated.

- *Macroptilium gracile* – this species demonstrated high production potential and to be highly diverse; the zone of adaptation is unclear
- *Macroptilium psammodes* CPI 39098 – Greater seed production and easier harvestability compared with other *Macroptilium* spp.
- *Lablab* - intermediate flowering types may be advantageous in many regions to complement late flowering *cv*. Highworth and early flowering *cv*. Rongai. Also some perennial accessions (CPI24973) were identified to be more persistent than cv. Endurance which may have a wider role as a short-term pasture.
- *Macroptilium bracteatum* – this species is known to have greater cold tolerance than other tropical legumes, so screening for improved cold tolerance (ongoing in private programs) would expand the range of this species further south into subtropical environments with longer frost periods.
- Diploid *Stylosanthes hamata*– potential to improve anthracnose tolerance and wider adaptation particularly on clay soils
- *Vigna parkeri* – screen lines for improved seed production in tropical latitudes; also early flowering for frost-prone regions of subtropics
- Subtropical *Stylosanthes* spp. for light soils (ATF 3076 and ATF3077) – revisit *in situ* collections that have persisted in old evaluation sites on infertile, sandy soils in southern inland Qld (Peck pers. comm.). Several lines of *S. seabrana* have been recorded to have high frost tolerance and production on light soils which may be higher than the commercial cultivars.
- Greater powdery mildew tolerance in annual medics – this screening and development is ongoing in SA but emerging material would require testing in the subtropics
- *Vigna lasiocarpa* – alternative to burgundy bean, with a larger seed which may enable easier establishment in cropping systems.
- *Alysicarpus rugosus* – some perennial options do exist and it is suited to sandy soils in northern semi-arid regions.

5.2.3 Priority regions and genera or species for investment

Based on the gap analysis above (Table 7), seven priority areas were identified where it was felt that further legume development could improve the range and application of legumes in northern pasture systems. These were (in order of priority):

1. Legumes that can reliably compete and persist in buffel grass (also other competitive grasses e.g. creeping blue grass, bambatsi panic) pastures. Some annual medics do fit this but only in southern Qld and production is highly variable. There is a lack of cold tolerant stylos or other tropical legumes that can fill this niche. *Desmanthus* and *Stylosanthes seabrana* have performed well in this region experimentally but have not been commercial successes.
2. Some options in higher rainfall areas (700-900 mm) (e.g. *Desmanthus*, Caatinga stylo) are constrained due to agronomic or productivity limitations. Agronomic solutions coupled with targeted evaluation/selection may overcome current adoption challenges in these species.

3. Legumes for clay soils in the far North (grey clays in Gulf) & central west Qld regions (Mitchell grasslands); This could extend into the Kimberley region as well.
4. Legumes for light soils (sandy and duplex soils) in southern inland subtropics where sown commercial grasses are common.
5. More robust perennial phase legumes in farming systems – targets would include larger seeded & higher N fixing alternatives to current burgundy bean (*Macroptilium bracteatum*) cultivars or a cold tolerant butterfly pea (*Clitoria ternatea*)
6. Legumes for the Wet Tropics region which can compete with vigorous grasses (e.g. *Brachiaria* pastures) – a few species are available (e.g. *Vigna parkeri*) but current cultivars have seed supply/cost constraints
7. Legumes for low rainfall western regions of Queensland, dry NT and WA (<600 mm) – no obvious options currently suited to these environments. Native legumes can grow very well but their presence is highly episodic and many contain toxic substances.

5.2.4 Other considerations for further development

Two other considerations were highlighted for further legume development work. These were:

- Agronomic traits (especially establishment) and grazing management are still major constraints to adoption of many 'adapted' legumes. Hence, any further development work needs to be coupled with research which deals with these important commercialisation constraints. Improved germplasm needs to be deployed in association with tested agronomic guidelines that maximise the likelihood of success.
- While there is temptation to develop new commercial species, there is likely to be greater success through exploring existing successful species/genera preferred for characteristics that widen their application or address key constraints to their adoption.

Allied issues for deliberation would be:

- Do current collections in the Australian Pasture Germplasm Collection have sufficient diversity of germplasm to facilitate improvement or screening? Would this require additional targeted collection of high priority genera?
- Which model for further pasture legume releases is likely to be used in the future- PBR or public varieties? This will influence the target end-point i.e. pre-breeding and further development via public-private partnerships.
- Screening priorities should consider the prospects of climate change with hotter and drier conditions expected in many regions, increasing the need for legumes resilient to more arid conditions.
- There is also growing interest in the use of summer-growing legumes in more southerly latitudes in NSW and western Australia – consideration is needed of the potential of current and new development opportunities.

6 Discussion

There has been significant historic progress in the evaluation, development and release of legumes for tropical pasture systems in Australia. In many key beef production regions there is a selection of legume cultivars available. However, in many cases the potential of these legumes has not been fully realised due to agronomic and management challenges (e.g. unreliable establishment, appropriate grazing management, low soil fertility especially phosphorus) and challenges to seed production systems. In many cases legumes were released in the past without follow-up research to help refine seed production agronomy and extend appropriate management guidelines for these legumes, which has resulted in sub-optimal performance and uptake on commercial farms. Significant gains are likely to be made through dedicated research to more fully explore the role, limitations and management of some of the newer released legumes (e.g. *Desmanthus virgatus*, *Stylosanthes seabrana*, *Macroptilium bracteatum*) to expand their use in northern Australia.

One of the greatest risks for progressing into a new phase of legume development or evaluation in northern Australia would be to lose and overlook the data and knowledge that has been developed in the past. This project has captured some of the highest priority legume evaluation data collected in northern Australia over the past 40 years, and this provides a valuable resource for refining or directing any future work. This resource also offers significant further potential for more detailed analysis using sophisticated statistical approaches that apply similar approaches to those used in the grains industry in national variety trial analysis. At the least the database can be interigated to gain information on relative performance of various accessions or species at specific or a set of evaluation sites.

This project has identified some potential areas where some renewal in legume development may be warranted to complement the array of legumes available for different soil types and production systems, to fill gaps where few legume options are available and to overcome key limiting attributes that would widen the application of successful legumes.

In order to reinvigorate further pasture legume development, an increase in research capacity is required. Over the past 10 years and in the coming 5 years, a large contingent of pasture scientists have retired and will retire, who will take with them much of the knowledge from pasture evaluation and research efforts in northern Australia over the past 20 years. This will leave fewer than 4 research scientists concerned with pasture research in the key agricultural research agencies servicing northern Australia. Some investment is required to grow capacity in pasture research to service the needs of the northern beef industry into the future. Without this, any wide-scale, coordinated and effective evaluation program will be limited.

6.1 The case for further pasture legume evaluation

There is a range of compelling evidence which shows the potential of pasture legumes to increase animal nutrition and pasture productivity. However, until recently there have been few analyses which have taken a holistic approach to evaluating the economic impact of legumes in northern beef production systems.

One was an analysis using a whole-farm systems model (NABSA) that is capable of simulating livestock production at the enterprise level, including reproduction, growth and mortality, based on energy and protein supply from natural C4- or buffel-grass pastures that are subject to high inter-annual climate variability (Ash et al. 2015). Using this model a range of development scenarios for northern beef production systems in 10 different regions were examined, including genetic gain in cattle growth and reproduction, nutrient supplementation, and alteration of the feed base through introduced pastures and forage crops. A scenario that aimed to quantify the net potential benefit that could be obtained through the augmentation of pastures with legumes was included. This assumed that a legume could be introduced into the grass-based pastures across the whole-farm enterprise and that establishment would be successful in the first year across the whole area. Only establishment costs were included and the costs of additional management or inputs to manage legumes in the pasture were not included.

This analysis revealed the very large potential impact that adding legumes to the pasture system can have on overall farm productivity and profitability across all environments in the northern beef industry (Table 8). These benefits arose through increased animal growth rates resulting in quicker turn-off of livestock and increased weaning rate through better breeding condition, which together greatly increased beef turn-off and overall farm profitability. These economic and production impacts were similar in scale to scenarios which combined improvements in breeder reproduction genetics, growth genetics, rumen modification and protein supplementation.

Table 8. Simulated whole-of-enterprise impacts of integrating legumes into beef production systems across northern Australia (adapted from Hunt et al. 2013). Simulations assumed most or all of the property was over-sown with perennial legumes similar to Stylos (investment cost $25/ha) which slowed the seasonal decline in protein and digestibility of pasture, allowed stocking rate (AE/ha) to increase somewhat due to higher pasture production but breeder numbers remain constant. In more developed regions (indicated with a #) 30-50% of the property was also sown to improved grass in addition to legumes.

Location/Region	Change in $ GM/ha	Change in $ GM/AE	% change in farm profit	% change in beef turn-off
Charters Towers	5.60	28.0	102	37
Duaringa #	12.3	39.0	114	20
Mitchell #	8.19	17.2	48	17
Gayndah #	15.8	45.0	86	17
Western Qld	8.65	34.5	86	32
Barkly	1.47	14.0	31	19
Victoria River	2.12	33.7	109	45
Central Aust	0.31	7.8	-247	19
Kimberley	2.95	50.7	623	58
Pilbarra	1.04	18.2	74	35

The second analysis is the report by Peck *et al*. (2011), who undertook analysis of the value of legumes for mitigating pasture rundown. They found that doubling the area of pastures with effective legume content to reach 3.6 M ha would result in an increase in NPV of the beef industry of $324 M over the next 10 years and over $1 billion over the next 30 (Peck et al. 2011). This is based on an assumption of approximately 10% adoption of legumes over the suitable areas in the northern beef industry – hence the NPV could be 10 times higher with industry-wide adoption of legumes in pastures.

Both these analyses clearly support the notion that legumes can have a large and ongoing impact on the profitability and productivity of beef production systems in northern Australia. Even modest gains in the adoption of legumes can have large returns for northern beef producers. Further whole-of-system analysis to more rigorously establish the value proposition for livestock enterprises of integrating legumes into various pasture systems in northern Australia and to account for risks and uncertainties is warranted.

6.2 Proposed paths for renewed legume evaluation & development

Based on the status of legume evaluation reported here, there appears to be three prospective lines of development (see Figure 18). Firstly there are several new cultivars that have been released recently (e.g. Progardes Desmanthus, psyllid resistant Leucaena) as well as some previously release material that require refinement of the agronomic package, wider testing and demonstration to maximise their acceptance and adoption. Secondly, a range of promising material has been identified in previous work that has not been further examined (see section 4.2.2 above). This material could progress into a field evaluation program aimed at comparing this material to existing cultivars and, where advantages are clearly evident, progress this material towards commercialisation. Finally, in some environments (see section 4.2.3) some new or novel germplasm may need to be examined in addition to other likely candidates in order to identify if any potential alternative species have potential to fill gaps in the array of options available (e.g. arid inland regions). In all cases there is interest and necessity to develop effective public-private relationships in order to target required attributes, circumvent issues related to economical seed production and agronomic management recommendations.

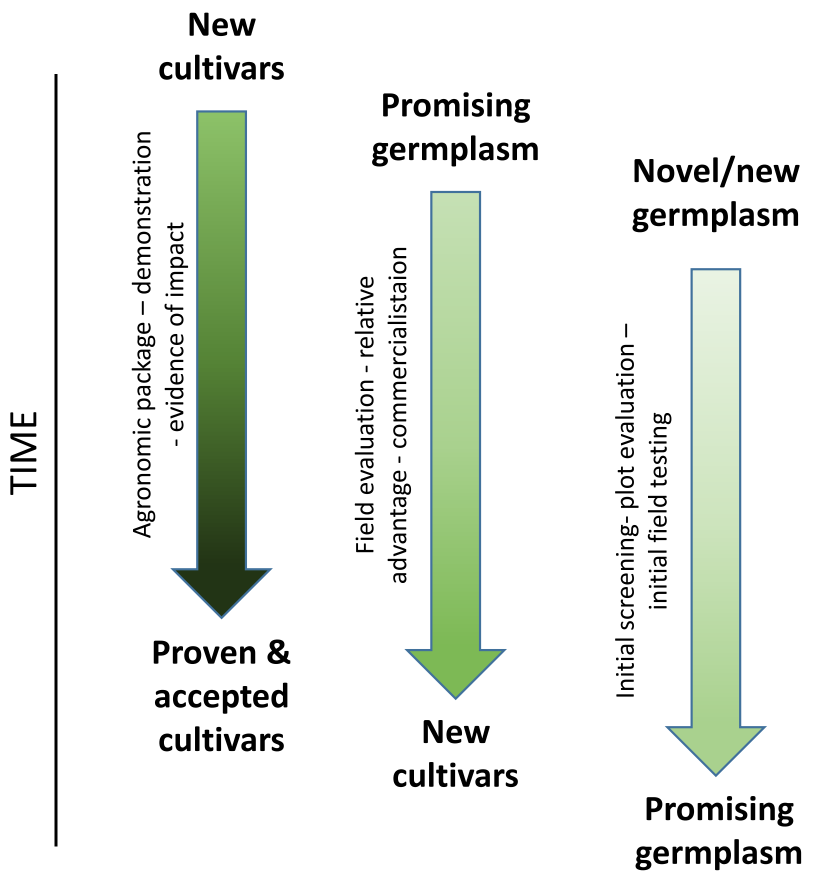

Figure 15. Pathways for further pasture legume development in northern Australia.

7 Conclusions

There is great potential to further build on pasture legume evaluation work conducted in northern Australia. The database of historical legume evaluation developed here enabled the first cross-site genotype × environment analysis of pasture legume performance in northern Australia. This revealed some species (e.g. *Macrotillium lathyroides*) and genera (e.g. *Desmanthus*) which performed well across a range of environments and warrant further investigation. However, this analysis only focussed on analysis at the species level of biomass yield related traits, and further in-depth analysis of accession performance in species or genera of interest and for a wider range of traits of interest is likely to be valuable.

Several regions have a variety of suitable legumes, though in many cases agronomic factors or seed production issues constrain their wider adoption. The more arid regions (e.g. western Queensland, southern NT and northern WA) have few if any suitable legumes but the potential to identify suitable species and demand for this technology is likely to be low. The greatest potential gaps in the current array of legumes is in the brigalow belt of southern and central Queensland and on clay soils in North Queensland and NT, where current commercial material has not been adopted due to agronomic and environmental constraints.

Highest priorities for further legume development identified were i) legumes that persist in competitive grass pastures in the subtropical semi-arid inland, and sub-humid coastal hinterland, ii) legumes for clay soils in northern tropical regions, iii) legumes for light soils (sandy and duplex) in inland subtropics, and iv) more robust ley legume options. Several species and accessions that have shown promise in past evaluation work and are thought to have attributes which improve on key limitations of commercial varieties but are not yet commercialized were identified in *Desmanthus*, *Stylosanthes, Macroptilium*, and *Aeschynomene*.

8 Key messages

- In many regions of northern Australia robust agronomically successful legumes are required in order to improve production efficiency of beef enterprises.
- While a range of varieties are available many have agronomic attributes, seed supply issues, or inability to tolerate soil or climatic conditions which limit their wider adoption
- Integrated analysis of historic legume evaluation data has revealed evidence of potential legume species (e.g. *Macroptillium lathyroides*) and genera (e.g. *Desmanthus*) which performed well across a range of environments which warrant further investigation.
- Data from historic legume evaluation work across northern Australia was at risk of being lost but has now been collated into a database to be used to guide any future legume evaluation programs.

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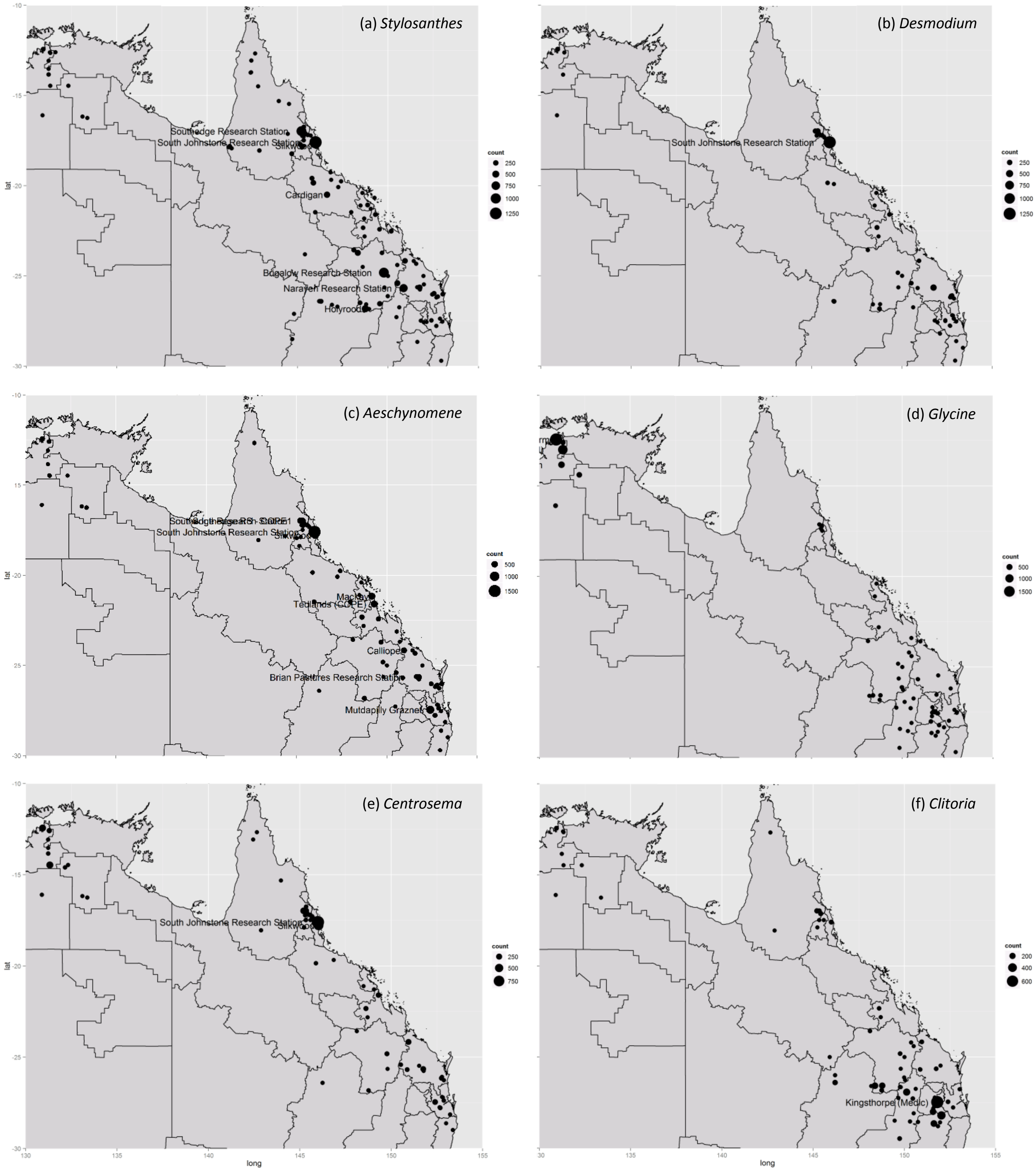
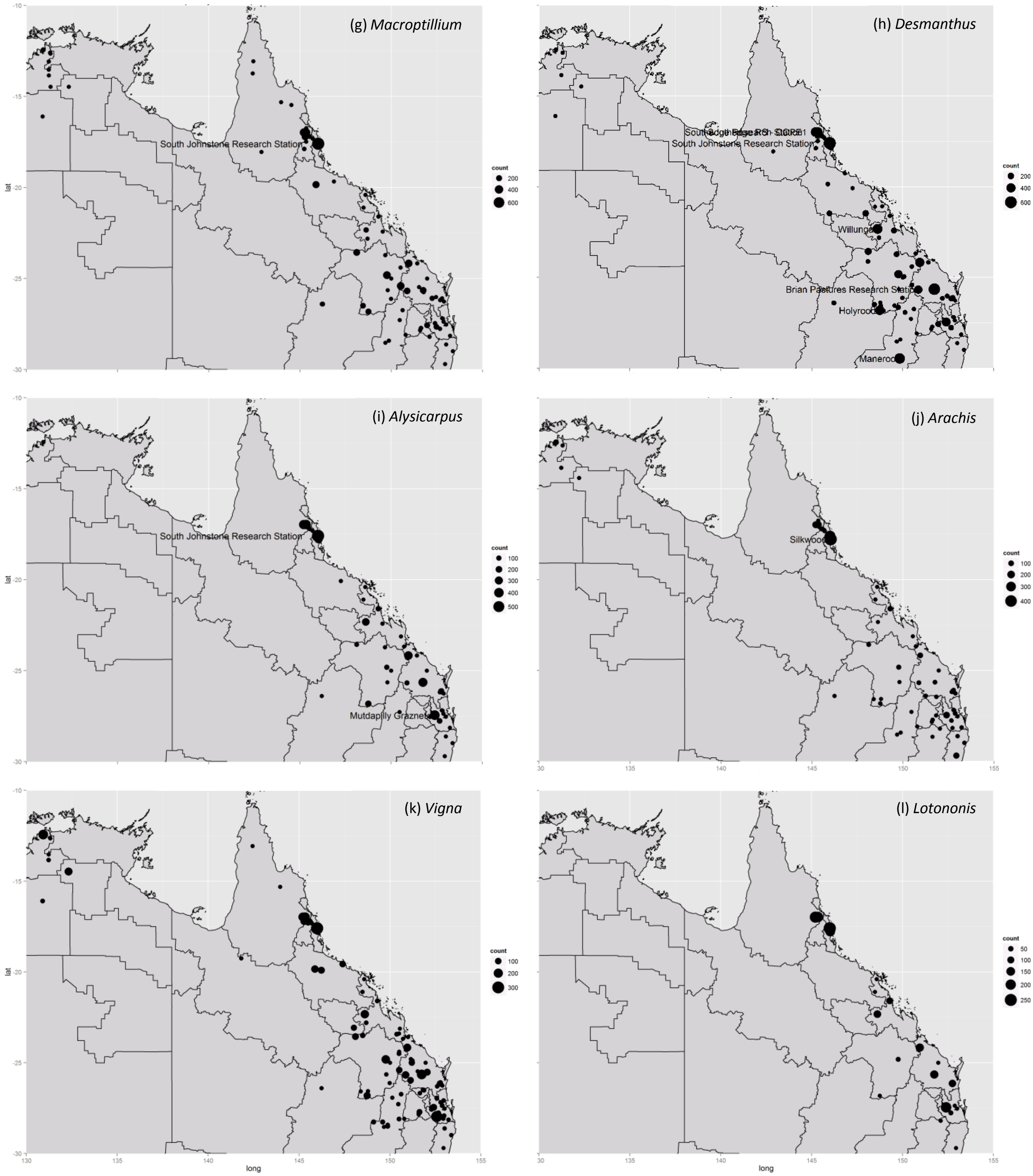
Appendix A. Intensity and distribution of pasture legume



evaluation in tropical and sub-tropical Australia.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(j) *Arachis*
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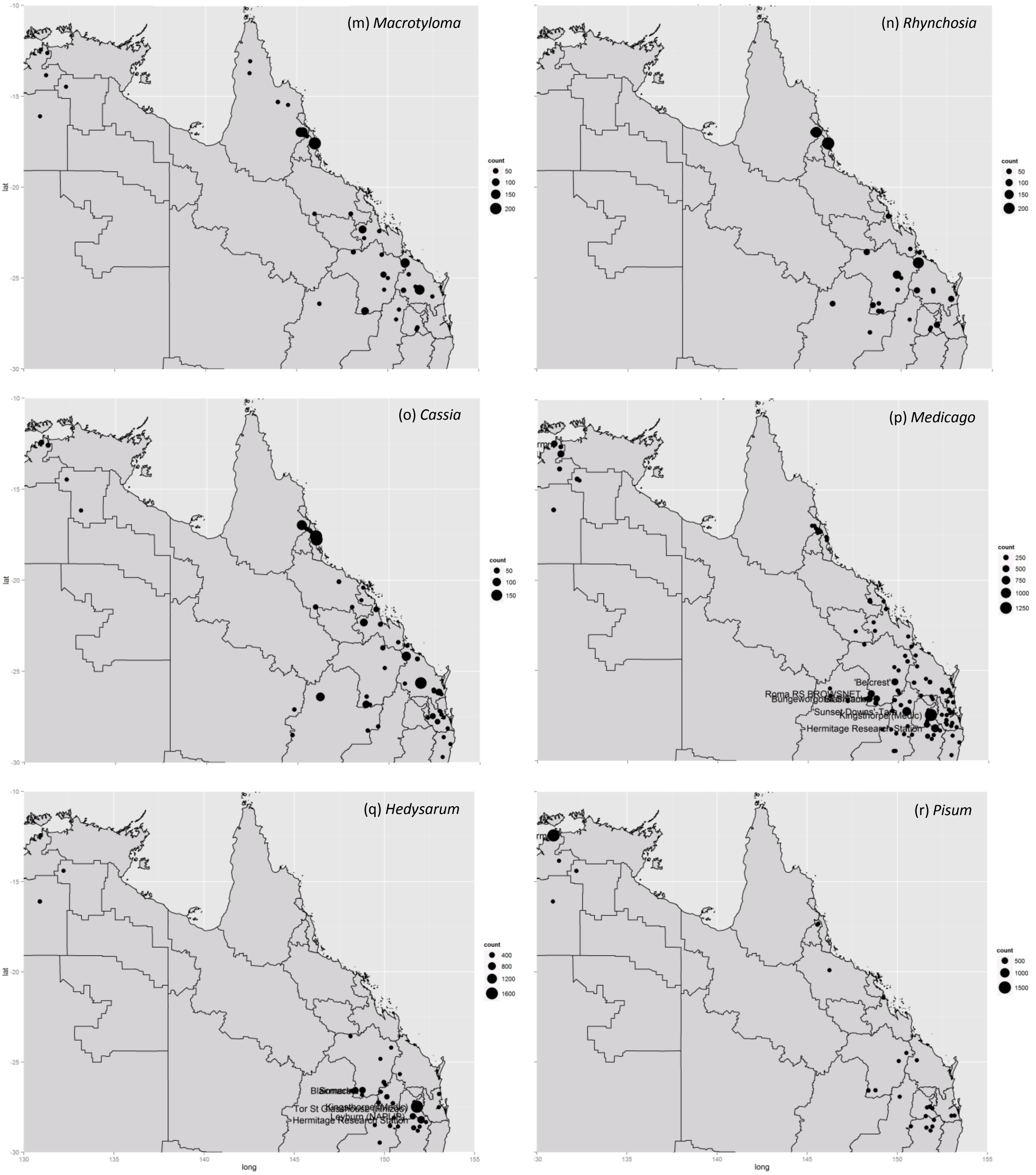

Figure A1. Maps indicating the locations and intensity (i.e. number of accession.years with recorded observations) of data contained in the database on the most evaluated tropical (a-o) and temperate (p-r) legume genera in northern Australia.
Note that the scale of dotes on each graph differs.

Appendix B. Abbreviations of species names

Table 9. List of tropical legume species and abbreviations included in meta-analysis

Species	Abbreviation	Species	Abbreviation
Aeschynomene americana	Asc.amr	*Cassia pilosa*	Css.pls
Aeschynomene brasiliana	Asc.brasln	*Cassia rotundifolia*	Css.rtn
Aeschynomene brevifolia	Asc.brv	*Centrosema acutifolium*	Cnt.act
Aeschynomene elegans	Asc.elg	*Centrosema brasilianum*	Cnt.brslnm
Aeschynomene falcata	Asc.flct	*Centrosema pascuorum*	Cnt.psc
Aeschynomene filosa	Asc.fls	*Centrosema plumieri*	Cnt.plm
Aeschynomene histrix	Asc.hst	*Centrosema pubescens*	Cnt.pbs
Aeschynomene indica	Asc.ind	*Centrosema sagittatum*	Cnt.sgt
Aeschynomene paniculata	Asc.pnc	*Centrosema schottii*	Cnt.scht
Aeschynomene sensitiva	Asc.sns	*Centrosema virginianum*	Cnt.vrgn
Aeschynomene sp.	Asc.sp.	*Chamaecrista fasciculata*	Chm.fsc
Aeschynomene villosa	Asc.vll	*Chamaecrista rotundifolia*	Chm.rtn
Alysicarpus bupleurifolius	Aly.bpl	*Clitoria sp.*	Clt.sp.
Alysicarpus longifolius	Aly.lngf	*Clitoria ternatea*	Clt.trn
Alysicarpus monilifer	Aly.mnl	*Cyamopsis senegalensis*	Cym.sng
Alysicarpus rugosus	Aly.rgs	*Desmanthus acuminatus*	Dsmn.acm
Alysicarpus vaginalis	Aly.vgn	*Desmanthus bicornutus*	Dsmn.bcr
Arachis burkartii	Arc.brk	*Desmanthus covillei*	Dsmn.cvl
Arachis diogoi	Arc.dig	*Desmanthus fruticosus*	Dsmn.frtc
Arachis glabrata	Arc.glb	*Desmanthus illinoensis*	Dsmn.ill
Arachis paraguariensis	Arc.prg	*Desmanthus leptophyllus*	Dsmn.lpt
Arachis pintoi	Arc.pnt	*Desmanthus pernambucanus*	Dsmn.prnm
Arachis pusilla	Arc.psl	*Desmanthus pubescens*	Dsmn.pbs
Arachis repens	Arc.rpn	*Desmanthus subulatus*	Dsmn.sblt
Arachis rigonii	Arc.rgn	*Desmanthus tatuhyensis*	Dsmn.tth
Arachis sp	Arc.sp	*Desmanthus virgatus*	Dsmn.vrgt
Arachis stenosperma	Arc.stn	*Desmodium adscendens*	Dsmd.ads
Arachis villosa	Arc.vll	*Desmodium barbatum*	Dsmd.brb
Cassia biensis	Css.bnss	*Desmodium canum*	Dsmd.cnm
Cassia biflora	Css.bfl	*Desmodium distortum*	Dsmd.dst
Cassia falcinella	Css.flcn	*Desmodium gangeticum*	Dsmd.gng
Cassia mimosoides	Css.mms	*Desmodium heterocarpon*	Dsmd.htrc
Cassia patellaria	Css.ptl	*Desmodium intortum*	Dsmd.int

Species	Abbreviation	Species	Abbreviation
Desmodium maxonii	Dsmd.mxn	*Rhynchosia aurea*	Rhy.aur
Desmodium molliculum	Dsmd.mll	*Rhynchosia balanse*	Rhy.bln
Desmodium pringlei	Dsmd.prng	*Rhynchosia candida*	Rhy.cnd
Desmodium procumbens	Dsmd.prc	*Rhynchosia caribaea*	Rhy.crb
Desmodium salicifolium	Dsmd.slc	*Rhynchosia cyanosperma*	Rhy.cyn
Desmodium scorpiurus	Dsmd.scr	*Rhynchosia densiflora*	Rhy.dns
Desmodium setigerum	Dsmd.stg	*Rhynchosia hirta*	Rhy.hrt
Desmodium sp.	Dsmd.sp.	*Rhynchosia hondurensis*	Rhy.hnd
Desmodium subsericeum	Dsmd.sbs	*Rhynchosia micrantha*	Rhy.mcr
Desmodium uncinatum	Dsmd.uncntm	*Rhynchosia minima*	Rhy.mnm
Desmodium velutinum	Dsmd.vlt	*Rhynchosia oblatifolia*	Rhy.oblt
Dolichopsis paraguariensis	Dlchp.prg	*Rhynchosia schimperi*	Rhy.schm
Dolichos trilobus	Dlchs.trlbs	*Rhynchosia sp.*	Rhy.sp.
Galactia tenuiflora	Glc.tnf	*Rhynchosia sublobata*	Rhy.sblb
Indigofera schimperi	Ind.schm	*Rhynchosia totta*	Rhy.ttt
Lablab purpureus	Lbl.prp	*Rhynchosia verdcourtii*	Rhy.vrd
Lotononis angolensis	Ltn.ang	*Stylosanthes capitata*	Sty.cpt
Lotononis bainesii	Ltn.bans	*Stylosanthes guianensis*	Sty.gnn
Lotononis heterophylla	Ltn.htrp	*Stylosanthes hamata*	Sty.hmt
Macroptilium atropurpureum	Mcrp.atr	*Stylosanthes scabra*	Sty.scb
Macroptilium fraternum	Mcrp.frtr	*Stylosanthes seabrana*	Sty.sbr
Macroptilium gibbosifolium	Mcrp.gbb	*Stylosanthes sympodialis*	Sty.sym
Macroptilium gracile	Mcrp.grc	*Tadehagi triquetrum*	Tdh.trq
Macroptilium lathyroides	Mcrp.lth	*Teramnus labialis*	Trm.lbl
Macroptilium longipedunculatum	Mcrp.lngp	*Teramnus micans*	Trm.mcn
Macroptilium martii	Mcrp.mrt	*Teramnus repens*	Trm.rpn
Macroptilium psammodes	Mcrp.psm	*Teramnus sp.*	Trm.sp.
Macroptilium sp.	Mcrp.sp.	*Teramnus uncinatus*	Trm.uncnts
Macrotyloma axillare	Mcrt.axl	*Uraria lagopodoides*	Urr.lgp
Macrotyloma daltonii	Mcrt.dlt	*Vigna adenantha*	Vgn.adn
Macrotyloma maranguense	Mcrt.mrn	*Vigna decipiens*	Vgn.dcp
Macrotyloma uniflorum	Mcrt.unf	*Vigna hosei*	Vgn.hos
Psophocarpus tetragonalobus	Psp.ttr	*Vigna lasiocarpa*	Vgn.lsc
Pueraria phaseoloides	Prr.phs	*Vigna luteola*	Vgn.ltl
Pycnospora lutescens	Pyc.lts	*Vigna oblongifolia*	Vgn.obln
Rhynchosia americana	Rhy.amr	*Vigna parkeri*	Vgn.prk

Species	Abbreviation	Species	Abbreviation
Vigna racemosa	Vgn.rcm	*Vigna trilobata*	Vgn.trlbt
Vigna schimperi	Vgn.schm	*Vigna unguiculata*	Vgn.ung
Vigna sp.	Vgn.sp.	*Vigna vexillata*	Vgn.vxl
Vigna sublobata	Vgn.sblb		

Table 10. List of temperate legume species and abbreviations included in meta-analysis

Species	Abbreviation
Hedysarum coronarium	Hdy.crn
Hedysarum flexuosum	Hdy.flx
Lathyrus aphaca	Lth.aph
Lathyrus cicera	Lth.ccr
Lotus jacobaeus	Lts.jcb
Medicago littoralis	Mdc.ltt
Medicago polymorpha	Mdc.ply
Medicago sativa	Mdc.satv
Medicago truncatula	Mdc.trn
Medicago x varia	Mdc.xvr
Pisum sativum	Psm.stvm
Tetragonolobus palaestinus	Ttr.pls
Trifolium cherleri	Trf.chr
Trifolium dichroanthum	Trf.dch
Trifolium hirtum	Trf.hrt
Trifolium leucanthum	Trf.lcn
Trifolium montanum	Trf.mnt
Trifolium pallidum	Trf.pll
Trifolium pratense	Trf.prt
Trifolium purpureus	Trf.prp
Trifolium repens	Trf.rpn
Trifolium squamosum	Trf.sqm
Trifolium subterraneum	Trf.sbt
Trifolium tumens	Trf.tmn
Trigonella calliceras	Trg.cll
Vicia narbonensis	Vic.nrb