The contribution of vegetation survey and mapping to Herbarium collections and botanical knowledge: a case study from Queensland.

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Abstract: The Queensland Herbarium Regional Ecosystem Survey and Mapping (QHRESM) program has contributed almost 90000 (89389) specimens to the Queensland Herbarium in Brisbane accounting for 28% of the specimens added to the Herbarium between 1970 and 2011. These specimens have been collected across all bioregions and vegetation communities in Queensland in a systematic sampling program driven by the requirement to sample comprehensively all vegetation communities. The QHRESM's Queensland Herbarium (BRI) specimens represent more than 79% of the native, and 73% of the naturalised vascular flora of Queensland, as well as making valuable contributions to the bryophytes, lichens and liverworts collections. The data and specimens collected enhance our ability to assess local, state and continental-scale plant diversity, and will be used by botanists, ecologists, governments, business and the public for long into the future.

Key words: conservation status, floristic composition, Herbarium specimens, modelling of species, Queensland flora, systematic sampling, regional ecosystems, survey and mapping, vegetation

Introduction

Since the late 1940s Australian vegetation scientists have developed a wide variety of vegetation survey, classification and mapping systems (Benson 1995, Sun *et al.* 1997). Vegetation surveys may target the occurrence of certain plant species or all species present at a site, and range from surveys for individual threatened plant species or specific taxonomic groups, where only certain plants are targeted, through to comprehensive site surveys where all species are documented (Thackway *et al.* 2008).

Vegetation mapping projects vary in scope and comprehensiveness and in the type of outputs produced. For some projects vegetation maps and associated descriptions are the only products, e.g. the mapping of the vegetation of Western Australia by John Beard (1979), and the vegetation map of Fraser Island (Stanton, 1979). However, vegetation survey and mapping projects can also collect large amounts of systematic ecological data with a wide range of applications, e.g. underpinning benchmarks and technical descriptions for biodiversity offsets, evaluating distribution and conservation status for species listing under legislative provisions, identifying species-rich areas for conservation planning and acquisition, as well as for basic scientific studies in plant systematics and ecology.

Queensland has a diverse range of landscapes, vegetation and ecosystems in its extensive 1,730,000 km² area. Queensland vegetation ranges structurally from rainforests in the Wet

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Tropics bioregion to sparse-forblands and open-hummock grasslands in the Channel Country bioregion (Sattler and Williams 1999). The development of a systematic and efficient method of mapping and surveying Queensland's diverse regional ecosystems has been refined over a number of years (Neldner *et al.* 2012, Neldner and Butler 2008). However, from the outset, the Queensland Herbarium Regional Ecosystem Survey and Mapping program (QHRESM) program has always been seen as an opportunity to obtain a comprehensive and systematic survey of the vegetation of Queensland, providing detailed floristic and structural data that can be used for a number of purposes as described above. The minimum field data required for ground truthing for mapping purposes is limited to the ecologically dominant layer, for example in wooded communities the tree layer (Neldner and Howitt 1991). The detailed vegetation site data form CORVEG, (the Queensland Herbarium ecological site database, which currently includes data from 12,502 validated and 7,075 unvalidated sites (Neldner *et al.* 2012). Collecting to improve knowledge of the distribution of Queensland's plants and vouchering specimens to confirm plant identities (all threatened plants and any new records for a 1:100 000 map sheet) has also been part of the methodology and has contributed a large number of specimens to the Queensland Herbarium.

In this paper, the contribution of the QHRESM program to knowledge of the Queensland flora through the provision of botanical specimens is examined. The QHRESM program includes all projects since 1970 that result in the production of a vegetation or regional ecosystem paper map or digital map coverage at a variety of scales (eg. 1:25 000 coastal mapping through to 1:1 000 000 scale western region mapping), and frequently with a report describing the map legend and vegetation units. The program also includes surveys of particular restricted vegetation types, such as groundwater springs (Fensham and Fairfax 2000), semi-evergreen vine thickets (Fensham 1995) and Astrebla grasslands (Fensham *et al.* 2000) that did not necessarily produce a final vegetation map of all communities.

History of Queensland Herbarium Regional Ecosystem Survey and Mapping (QHRESM)

Botanists from the Queensland Herbarium provided ecological input into the multi-disciplinary CSIRO Land Research Series and Western Arid Region Land Use Study (WARLUS) in Queensland in the 1960–1970s. A vegetation mapping program for Queensland was devised and implemented with the assistance of Commonwealth funds through the Australian Biological Resources Study in the late 1970s (Neldner 1993a).

From 1970 to 1979, the Queensland vegetation mapping program was predominantly involved in the WARLUS (1:1 M scale), coastal mapping for the Beach Protection Authority (1:25 000), and the Moreton Region Vegetation Map Series (1:100 000). In the period of 1980 to 1994, large areas of western Queensland were mapped through the Vegetation Survey of Queensland (1:1 M), together with the Cape York Peninsula Land Use Study (1:100 000),

Mackay coast mapping (1:25 000), Darling Downs mapping, Desert Uplands bioregion mapping and continued Southeast Queensland mapping. From 1995 to 1997, there was an active period of mapping in Southeast Queensland under the Forest Agreement process (McAlpine *et al.* 2005), together with the commencement of regional ecosystem (see Sattler and Williams 1999) mapping in the Brigalow Belt, Einasleigh Uplands and Bartle Frère 1:100 000 map sheet of the Wet Tropics, and surveys of the Mitchell grass, artesian springs and serpentine areas of Queensland. In the final period since 1998, regional ecosystem mapping program activity has concentrated on the eastern bioregions and through the Gulf Plains and Northwest Highlands bioregions.

Forty-three years since its commencement, the mapping of Queensland's vegetation and regional ecosystems is 95% completed at 1:100 000 or larger scale, and 1386 regional ecosystems have been defined and mapped (Queensland Government 2012). The coverage of regional ecosystems across both pre-cleared environments and remnant vegetation is readily available on the Queensland Government data website (https://data.qld.gov.au/) and has been used increasingly by government, business, landholders and the community for a wide variety of planning (e.g. biodiversity planning assessments for bioregions), regulatory (eg. tree clearing under the Vegetation Management Act 1999), fire hazard risk assessment, and educational uses.

Methods

The Queensland Herbarium (International Herbarium acronym BRI, ie. short for Brisbane) was one of the first herbaria in Australia to document its specimens in a database, HERBRECS (Johnson 1991). HERBRECS is a corporate Oracle database consisting of 826,374 specimen records (on 7th November 2013). HERBRECS was interrogated on the basis of the primary specimen collector to find those specimens collected during survey and mapping projects in Queensland in the last 43 years. Most of the selected collectors were primarily involved in survey and mapping projects on a full time basis; all specimens collected by them could be attributed to this activity. However, some collectors were involved in a number of different projects or submitted specimens collected in a private capacity. These collections were excluded with the aid of ArcGIS mapping software to identify collections not associated with the program. The author, who was part of the QHRESM program from 1980 and managed the program from 1996 to 2004, used his knowledge of the collectors and their projects to refine the selected list down to those attributable to survey and mapping projects. Once the specimens that were attributed to survey and mapping activities were distinguished, they were analysed by criteria including taxonomic family, genera, date of collection, conservation status and native status. The data manipulation, statistical summarisation and graphics production were performed within the R computing environment (http://www.r-project.org/).
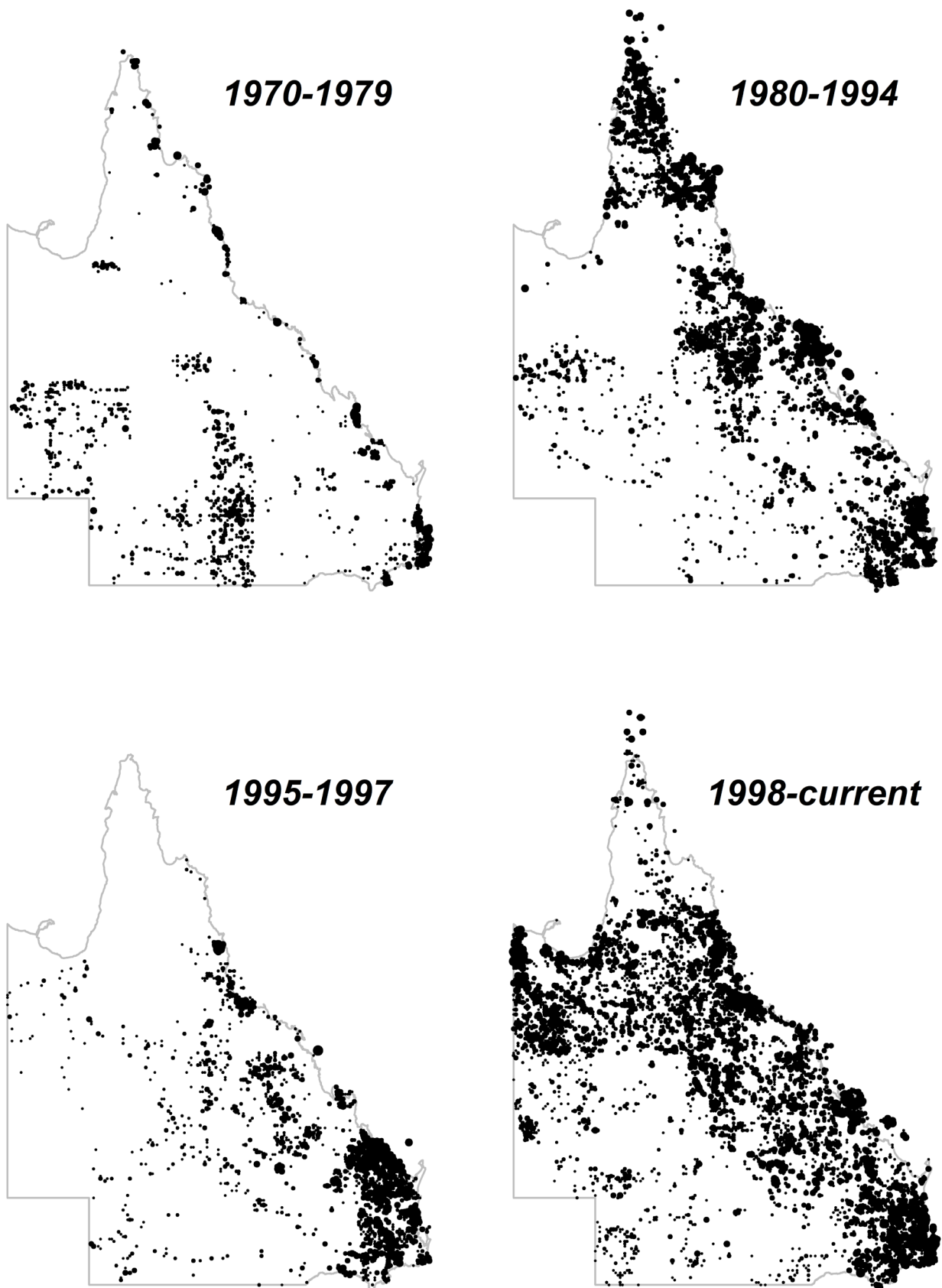
Fig. 1. Geographic distribution and density of BRI Herbarium specimens collected during significant phases of the QHRESM program. The number of specimens in each 80 km² grid cell (0.083 degree latitude by 0.083 degree longitude) was calculated. For each cell, the dot size is proportional to the logarithm of the specimen count.

The geographic distributions of the specimens collected during the QHRESM program were mapped on the basis of relevant periods (years collected) and the density of collections (Figure 1) using the count of specimens for each 80 km^2 grid cell (0.083 degree latitude by 0.083 degree longitude). This map illustrates the distribution and intensity of collecting of BRI specimens through the QHRESM program for various time periods.

Results

About 50 botanists and technicians involved in QHRESM projects have lodged specimens at BRI Herbarium. About 20 collectors each with more than 1000 BRI specimens from the QHRESM program are listed individually in Table 1 together with the number of specimens lodged; a combined number is given for other collectors. For all collectors, the specimens that were not collected as part of QHRESM program have been removed from the analysis.

Also listed in Table 1 are data on the conservation (E = Endangered, V = Vulnerable, NT = Near Threatened, LC = Least Concern listing under the *Nature Conservation Act 1992*) and native status of the taxa. Specimens from 369 families were collected during the program from 1970–2011, with the majority being vascular plants and least concern (LC) native species.

Table 2 lists the number of specimens collected as part of the QHRESM program listed alphabetically by family (where >1000 specimens), and other plant groups. The QHRESM BRI Herbarium collections made up 28% of the overall collections for native plants, 31% of the non-native plant collections and only 16.5% of the threatened plant specimens. For all of the largest Angiosperm families at least 20% of the specimens came from QHRESM, with higher proportions (>30%) from the Poaceae, Cyperaceae, Malvaceae and Chenopodiaceae. These families generally dominate the ground layer and frequently require identification in the laboratory. The QHRESM specimens made up a higher proportion (31%) of non-native specimens collected and a lower proportion of threatened taxa (16%).

The number of species collected by the QHRESM program is compared to the total flora for Queensland as documented by Bostock and Holland (2010) for the major plant groups in Table 3, and the largest families and genera in Table 4.

The frequency of Angiosperm taxa collected as part of QHRESM program and lodged as BRI Herbarium specimen ranges from 943 taxa represented by only a single specimen, to taxa represented by more than 100 specimens (Table 5) not included in Figure 2.

The number of specimens added to BRI by the QHRESM program from 1970 to 2011 was 89 389 specimens (28% of the total of 316 982). Figure 2 shows the number of specimens

Table 1. Primary collector and number of QHRESM specimens by Threat status, non-native and undescribed taxa status incorporated as BRI Herbarium specimens from collections made during the survey and mapping program up to December 2011.
Threat status E = Endangered, V = Vulnerable, NT = Near Threatened, LC = Least Concern listing under the *Nature Conservation Act 1992*. Undescribed taxa = specimens assigned to a genus and phrase name

Primary Collector	Total	E	V	NT	LC	Non-native	Undescribed taxa
Bean A.R.	14897	94	214	159	12068	2362	117
Batianoff G.N.	12448	19	89	112	9726	2502	66
Thompson E.J.	10365	20	53	79	9506	707	270
Clarkson J.R.	5906	6	41	50	5493	316	80
Fensham R.J.	5863	53	63	48	5202	497	79
Cumming R.J.	3971	8	21	63	3469	410	55
Booth R.	3180	2	7	22	3030	119	88
Neldner V.J.	2822	0	8	15	2620	179	39
Fox I.D.	2452	1	4	10	2212	225	23
Fell D.G.	2386	2	27	65	2259	33	76
Grimshaw P.G.	2320	24	66	92	2107	31	29
Pollock A.B.	2177	4	16	15	1898	244	15
McDonald W.J.	2144	10	43	84	1943	64	27
Stephens K.M.	1930	4	7	14	1669	236	8
Kemp J.E.	1922	3	6	13	1764	136	28
Johnson D.C.	1332	0	4	1	1265	62	14
Purdie R.W.	1350	0	5	5	1306	34	22
Hunter J.T.	1284	2	22	82	1158	20	45
Turpin G.P.	1157	0	1	7	1102	47	16
Other^	9483	45	81	79	8477	801	110
TOTAL	**89389**	**297**	**778**	**1015**	**78274**	**9025**	**1207**

^Other includes the BRI collections of Addicott E.P., Appelman C.N., Bailey L., Baumgartner D.J., Beeston, G.R., Boyland, D.E., Brushe J., Butler D.W., Cartan H., Dillewaard H.A., Dowling R.M., Durrington, L., Edginton M.A., Elsol J.A., Fairfax R.J., Horton S.A., Kahler C., Kelman D.T., Lovatt R., McDonald T.J., Pennay C., Richter D., Ryan T.S., Schmeider M., Sparshott K.M., Sullivan S.C., Thompson S.L., Wilson B.A., Wilson G.W. and Young P.A.

Table 2. Number of QHRESM specimens (total 89383) listed by major plant family or taxonomic group, showing number of native, non-native and Threatened (E,V,NT) specimens and the proportional contribution to the total BRI Herbarium specimen collections (for 1970-2011).

Family	No. of native	% of total native	No. of non-native	% of total non-native	No. of E, V, or NT	% of total E, V or NT
Poaceae	11292	42.5	1733	24.5	126	26.3
Myrtaceae	6160	27.7	54	38.0	329	22.5
Cyperaceae	5380	39.4	238	32.2	35	23.0
Fabaceae	5310	28.2	823	25.0	47	20.9
Mimosaceae	3508	24.4	155	22.0	123	17.3
Asteraceae	3226	30.2	1287	24.5	107	27.9
Rubiaceae	1857	24.3	113	22.1	26	12.7
Malvaceae	1658	35.8	406	28.3	3	42.9
Sapindaceae	1543	24.5	35	24.3	50	12.6
Euphorbiaceae	1520	24.8	209	22.2	62	15.5
Rutaceae	1382	20.7	20	35.1	80	12.9
Phyllanthaceae	1374	28.1	20	20.6	30	15.7
Lamiaceae	1202	26.2	207	25.4	30	14.5
Apocynaceae	1167	21.5	234	28.7	72	21.9
Chenopodiaceae	1141	30.4	23	17.6	2	6.3
Proteaceae	1017	20.7	0	0	79	12.6
Other Angiosperms#	28782	25.7	3444	58.6	824	16.5
Gymnosperms	123	6.4	123	15.5	0	0
Pteridophyta	1819	11.2	24	5.6	27	6.4
Bryophyta	137	4.6	0	0	0	0
Lichens & Liverworts	522	3.9	0	0	38	0
Algae	47	3.5	0	0	0	0
Fungi	320	3.8	0	0	0	0
Total	**89389**	**28.2**	**9025**	**30.9**	**2090**	**16.5**

Other Angiosperms is represented by 257 families, Gymnosperms by 4 families, Pteridophytes by 34 families, Bryophytes by 17 families, Lichens and Liverworts by 40 families, Algae by 2 families, and fungi by 24 families.

Table 3. Major plant groups showing number of taxa collected by QHRESM program specimens compared to total for Queensland.

	Species identified from QHRESM program	Taxa identified from QHRESM program	QLD species (Bostock & Holland 2010)	% Qld species collected by QHRESM program	No. of BRI specimens
Native vascular	6549	6897	8449	78	77519
Naturalised alien	918	936	1258	73	9015
Angiosperms	6308	6665	8005	79	75758
Gymnosperms	41	41	62	66	121
Pteridophyta	187	190	381	49	1640
Bryophytes	25	25	555	5	43
Lichens & Liverworts	102	102	1309	8	198
Algae	10	10	1505	0.01	11
Fungi	47	47	na	na	71

Table 4. Number of taxa represented by QHRESM program specimens for selected families and genera with high species diversity, and comparison with total taxa for Queensland (Bostock & Holland 2010).

Family/genera	No of Species	No of Taxa	No of QLD species	% Qld species	No. of BRI specimens
Poaceae	550	579	629	87	11216
Myrtaceae	524	543	601	87	6202
Fabaceae	376	409	474	79	4866
Acacia + Vachellia	258	272	308	84	3121
Corymbia +Eucalyptus	212	225	222	96	3020

Table 5. Frequently recorded QHRESM program taxa with more than 100 specimens in BRI Herbarium

| Taxon	Family	No. of BRI specimens	No. of Bioregions recorded	No. of CORVEG records
Fimbristylis dichotoma (L.) Vahl	Cyperaceae	177	13	800
Cyanthillium cinereum (L.) H.Rob.	Asteraceae	146	12	1395
Eucalyptus crebra F.Muell.	Myrtaceae	145	10	1670
Aristida holathera Domin var. *holathera*	Poaceae	143	13	500
Alphitonia excelsa (Fenzl) Benth.	Rhamnaceae	132	12	1892
Enneapogon lindleyanus (Domin) C.E.Hubb.	Poaceae	123	12	463
Corymbia clarksoniana (D.J.Carr & S.G.M.Carr) K.D.Hill & L.A.S.Johnson	Myrtaceae	118	11	890
Panicum effusum R.Br.	Poaceae	108	13	710
Allocasuarina littoralis (Salisb.) L.A.S.Johnson	Casuarinaceae	107	8	648
Schizachyrium fragile (R.Br.) A.Camus	Poaceae	106	13	804
Cyperus difformis L.	Cyperaceae	105	13	88
Melaleuca viridiflora Sol. ex Gaertn. var. *viridiflora*	Myrtaceae	103	9	945

collected through the program each year compared to the total specimens incorporated into the Queensland Herbarium for the same year. Specimens from the program made up only 1% of the total number added to the Herbarium in 1973, up to a maximum of 49% of the specimens incorporated in 1994.

A large number of Angiosperm taxa were only collected and lodged in BRI by the QHRESM program a few times, while there were 12 species that were represented by more than 100 specimens in BRI. The frequency of BRI collection of individual Angiosperm taxa during the QHRESM program is illustrated in Figure 3.

As a measure of the geographic distribution of the QHRESM collections, the proportion of the total Herbarium specimens that are QHRESM collections in each of the 15 Pastoral Districts that make up Queensland is shown in Figure 4. At least 15% and up to 52% of BRI specimens for every Pastoral District were collected through the QHRESM program.

Discussion

The results compiled above (particularly Table 1, Figure 1) demonstrate the significant contribution the QHRESM program has had in increasing the knowledge of Queensland's vascular plants through the specimens housed in BRI. Since 1970, the survey and mapping projects have contributed 28% of all specimens collected for BRI. During the years of 1992–1999, when the concentrated vegetation mapping activity was occurring under the Cape York Peninsula Land Use Study (CYPLUS) and Southeast Queensland Forest Agreement (SEQFA), more than 40% of collections were from this program. The QHRESM specimens, together with collections from the biodiscovery plant collecting project (P.I. Forster collections 1994–2003 of 13,808 specimens),
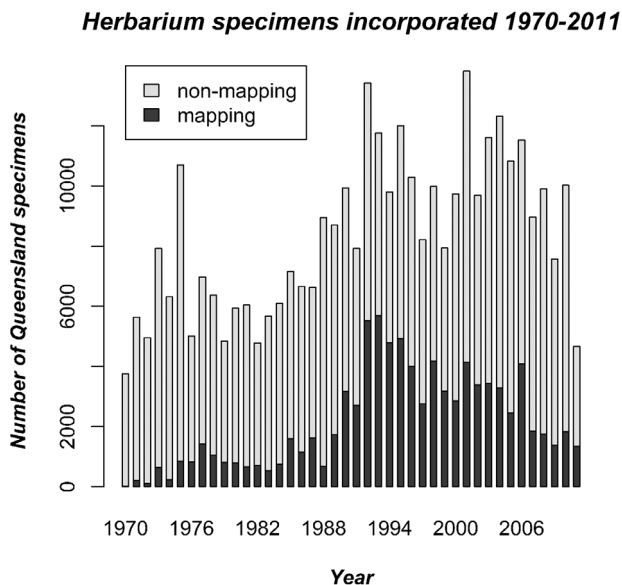
Fig. 2. Stacked bar chart of number of specimens collected through the QHRESM program by each year compared to the total specimens incorporated into BRI Herbarium for the same year.
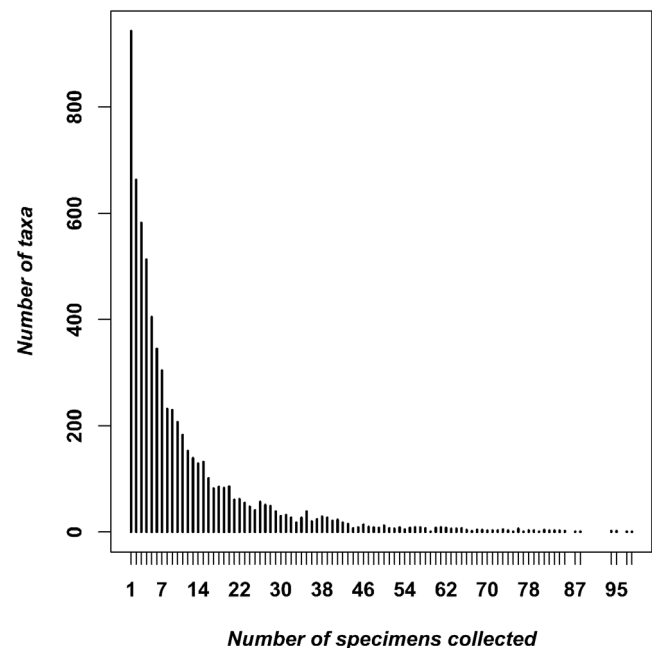

Fig. 3. Histogram of frequency of collection of individual Angiosperm taxa during the QHRESM program. 943 taxa were only collected once; 12 species collected more than 100 times are not included in this figure but are listed in Table 5.

accounted for more than 50% of accessions to the Queensland Herbarium during the 1994–2003 period. In addition to BRI specimens, duplicate specimens were also sent to other herbaria worldwide to further taxonomic study.

The QHRESM collections have provided a relatively comprehensive coverage of the overall vascular plant diversity of Queensland. For example over 77% of the described native and naturalised vascular flora has been collected (Table 3). For the largest families and genera, the QHRESM program plant collections represent more than 79% of the total Queensland flora, and for the eucalypts (*Corymbia + Eucalyptus*) and acacias (*Acacia + Vachellia*) which dominate and define the majority of wooded vegetation communities, the percentage representation is higher, greater than 83 and 95% respectively (Table 4).

The vegetation survey and mapping methodology (Neldner *et al.* 2012) requires the systematic assessment of all layers ie. tree, shrub and ground layers, and ensures that all life forms of vascular plants are inventoried. Table 2 shows a large number of families dominated by herbaceous species. While herbaceous species can frequently add a high number of overall species diversity at a site and are important for building effective surrogates for plant diversity in classification, they are not usually important for defining the vegetation community for mapping purposes, apart from in grasslands, forblands and sedgelands. The high number of herbarium specimens lodged from predominantly herbaceous dominated families indicates that botanists are recording the full vascular plant diversity at a site within the seasonal condition constraints.
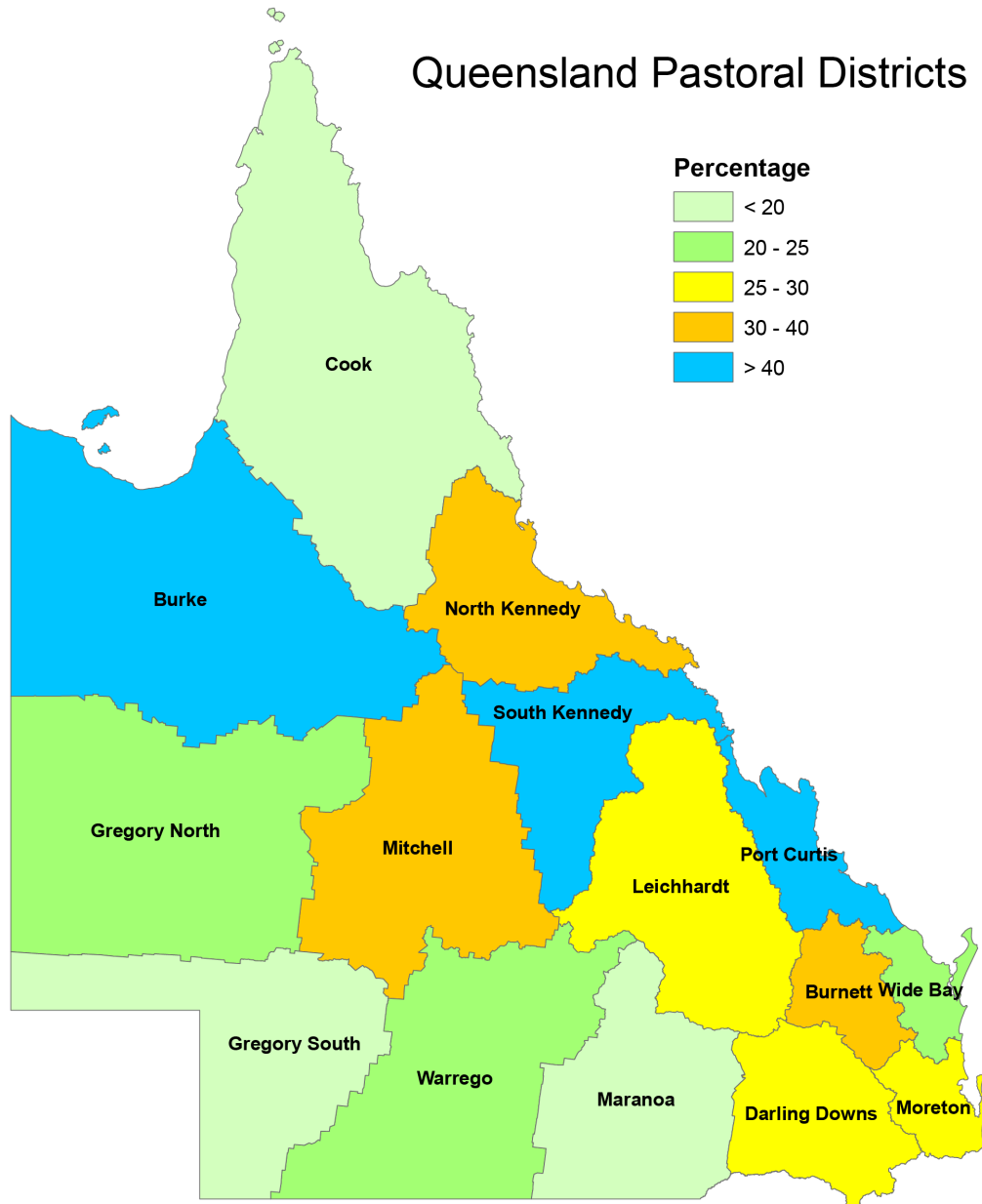
Fig. 4. Map of Queensland illustrating the proportion of BRI Herbarium collections derived from the QHRESM program in each Queensland Pastoral District.

Vascular plants dominate BRI Herbarium collections from the QHRESM program with 96% of the collections being Angiosperms, 0.15% Gymnosperms and 2.3% Pteridophytes. However while the scope of QHRESM is to describe the terrestrial vegetation, there have been significant collections of non-vascular plants: 137 mosses from 17 families, 522 lichens from 40 families, 47 Algae from 2 families, and 320 fungi from 24 families. The comprehensiveness of these non-vascular plants collections varies greatly, and is primarily driven by the interests of the individual botanist.

The QHRESM collections of the vascular flora are dominated by the Poaceae which frequently dominate the ground layer in terms of species and cover, and frequently require collecting for positive identification. Numerous collections have been made of Cyperaceae, Fabaceae, Asteraceae, Malvaceae, Euphorbiaceae, Chenopodiaceae and Phyllanthaceae which also contribute a large amount of species and cover to the ground layer. Prior to broad-scale clearing, 43% of Queensland was dominated by Eucalypt open forest and woodlands, while the semi-arid areas dominated by Acacia low woodlands and tall shrublands made up 23% of the state. By 2003 the remnant vegetation had been reduced to 33% and 16% respectively (Queensland Government 2008). Hence it is not surprising to see the numerous QHRESM collections of Myrtaceae and Mimosaceae. There are also frequent collections from families such as Myrtaceae, Rubiaceae, Sapindaceae, Rutaceae, Apocynaceae and Proteaceae that have a large number of representatives in the rainforests, which covered 1% of Queensland in 2003, about half of their pre-clearing distribution.

The QHRESM collections also reflect the plant diversity of Queensland's nearly 8500 native vascular plant species, the largest families of which are the Poaceae (629 species) Myrtaceae (601 species) and Fabaceae (474 species) (Bostock and Holland 2010) (Table 4). The 12 most frequently collected (> 100 specimens) species from the QHRESM program (Table 5) are all widely distributed and abundant species. Seven species are herbs (four Poaceae, two Cyperaceae and an Asteraceae) and occur in 12 or more of the 13 bioregions of Queensland. *Eucalyptus crebra* and *Corymbia clarksoniana* are widespread canopy trees (10 and 11 bioregions), while *Melaleuca viridiflora* (9) and *Allocasuarina littoralis* (8) can dominate the canopy or occur as subcanopy trees. *Alphitonia excelsa* (12) is usually a subcanopy tree. As well as being important for defining regional ecosystems, all of these tree species can show significant morphological variation, and these factors together with their widespread distribution explain the high BRI Herbarium specimen collection numbers.

During survey and mapping projects, many more specimens are collected than those that are eventually lodged in herbaria. Most are collected to confirm field identification and discarded once determination is resolved. Specimens of (conservation) least concern plants may be retained as vouchers or if there is no specimen for the taxa held in BRI Herbarium for the 1:100 000 map sheet area. Because of seasonal conditions at the time of surveys some specimens

are infertile or of too poor quality to be lodged. Figure 2 shows that the majority of taxa are collected less than 6 times by the QHRESM program. The validated CORVEG database consists of 12,502 sites and 272,899 taxa records with average of 26 species per site. Table 5 demonstrates that generally only 15% of the CORVEG records of the 12 most collected species are vouchered. This is appropriate given the cost of collecting, identifying, processing, curating and databasing voucher specimens. The current charge by Council of Heads of Australasian Herbaria (CHAH) is $110 per hour for plant identification and $30 for specimen preparation, databasing and curation.

Herbarium specimens are fundamental to taxonomic research. While it is very difficult to provide an estimate of how many new species were discovered through the QHRESM program, the number of specimens that are only determined to genus level can give some indication of the potential numbers. Queensland Herbarium standards for accepting specimens require them to be fertile specimens (apart from some rainforest specimens) and in a state that they can be identified to species level. From the total of 89,389 BRI specimens collected by the QHRESM program, 1321 specimens could only be identified to a genus, however a further 1207 specimens (1.4%) have a generic name and phrase name (Table 1), e.g. *Acacia* sp. (Ronlow Park E.J.Thompson+ 61), and are earmarked as a potentially undescribed taxon. Bebber et al. (2010) found that only 16% of new species were described within 5 years of first being collected, while the remaining 84% were described from older specimens, some more than 50 years old. The average time lag for angiosperms was 35 years (Bebber et al. 2014). Hence many of the QHRESM BRI specimens may not be critically examined by taxonomists for many years to come. However so far at least 21 Queensland species described in the last 20 years have been given names honouring botanists involved in the QHRESM program.

Herbarium specimens have a much greater use than only plant systematics. Increasingly specimens are being used to provide genetic material to examine the systematic relationships based on genetics (Herrmann and Hummel 1994) or preserve germplasm (Lister et al. 2010), or in some cases chemical analyses are conducted to examine the phytochemistry, eg. foliar Manganese accumulation (Fernanado et al. 2009) and lead-uptake; pollution documentation; bio-prospecting (Funk 2007). Other information that can be studied from Herbarium specimens includes plant predators e.g. leaf miners, leaf-cutter ants, plant diseases eg. myrtle rust, and fungal/ vascular plant symbionts (Funk 2007).

As well as adding to the number of specimens in BRI Herbarium, the QHRESM program has greatly improved the distribution of specimens because the ecological sampling for mapping is stratified to cover all of the different vegetation types present and also to sample across the whole map area. This helps to overcome some of the problems associated with herbarium specimens worldwide which have been found to be generally clumped around specific areas (Moerman and Estabrook 2006, Feeley and Silman 2011)

and biased towards species that are demographically rare in the field. Thus any estimates of species abundance based on herbarium specimens are inherently biased, and cannot be interpreted as being a predictor of their true abundance in the field (Garcillan and Ezcurra 2011). Table 2 shows that the QHRESM collections make up 28% of the total collections of native plants with a consistent rate of at least 20% of the collections across all the major Angiosperm families. However the lower rate of 16.5% for threatened plants supports the findings of a bias in general herbarium collections to demographically rare plants.

The survey and mapping methodology attempts to ensure all vegetation types are sampled based on their relative distribution in the landscape as determined from remotely sensed imagery (Neldner *et al.* 1995, 2012). Figure 1 shows the geographic distribution and density of QHRESM program BRI collections. It can be seen that the collections have been made across the whole of Queensland, including a large number of the offshore islands. This is supported by Figure 4 which demonstrates a consistent contribution of at least 15% (up to 52%) of the specimens for a Pastoral District coming from the QHRESM program. The focus areas of the QHRESM program at various time periods described earlier can be clearly seen in Figure 1.

High quality fertile specimens of many (conservation) Least Concern species collected in surveys are discarded after name verification, as there are already adequate specimens for that area in the herbarium. However for Threatened taxa, 2090 specimens (2.3% of all QHRESM collections) of species listed under the *Nature Conservation Act 1992* (http://www.legislation.qld.gov.au/LEGISLTN/CURRENT/N/NatureConA92.pdf) were lodged in the Herbarium to improve knowledge of the distribution of these threatened plants. 52% of the plant taxa listed as threatened have been collected by the QHRESM program with 95 species of Endangered, 224 species of Vulnerable and 244 species of Near Threatened plants collected. In Queensland, herbarium collections of listed species under the *Nature Conservation Act 1992* are buffered with the remnant vegetation coverage to provide the essential habitat coverage that is used in regulating clearing under the *Vegetation Management Act 1999* (http://www.legislation.qld.gov.au/LEGISLTN/CURRENT/V/VegetManA99.pdf).

Herbarium specimen and ecological site data are used to define the area of occurrence and extent of occupancy of species assessed under the IUCN criteria (IUCN 2001) to determine conservation status. The increased knowledge of the distribution of Queensland plants has been the primary factor that has allowed for the downgraded listing of 116 formerly *Nature Conservation Act 1992* listed species over the last 5 years. Neldner (1993b) documented how the additional specimen data collected through the Cape York Peninsula survey and vegetation mapping project led to the delisting of *Neofabricia mjoebergii, Neofabricia sericisepala* and *Decaschistia peninsularis*. Of the 18 Queensland plants de-listed from the Commonwealth *Environmental Protection and Biodiversity Conservation Act 1999* on 23 May 2013 and 14 December 2013 http://www.environment.gov.au/

cgi-tmp/publiclistchanges.5b2453194e7b93cb2e3f.html, all apart from *Commersonia argentea*, had at least one BRI specimen collected through the QHRESM program. Species with five or more QHRESM BRI specimens (Number of CORVEG site records in brackets) were *Acacia ramiflora* (16), *Bothriochloa biloba* (3), *Brachychiton vitifolius* (14), *Croton magneticus* (1), *Digitaria porrecta* (1) and *Jedda multicaulis* (1).

Herbarium specimen records are used extensively for modelling species distributions and scenarios such as the potential impacts of climate change. Rivers *et al.* (2011) have found that at least 15 specimen locations are required to build accurate range estimates of plant distributions, while Feeley and Silman (2011) found that extra specimens and more systematic collecting is required to accurately model and map species ranges. As can be seen in Figures 1 and 4, the QHRESM program has contributed a large amount of systematic data across Queensland, which is made available to governments, researchers and the general public world-wide through Australia's Virtual Herbarium, the Atlas of Living Australia and the Australian Ecological Knowledge and Observation System (AEKOS) (TERN 2013).

Species distribution and population models are useful for assessing the conservation status, population health and threats to species. Reliable locational data and specimen identification are core to achieving successful models. At each CORVEG site, measures of abundance are recorded for different plant lifeforms: basal area, stem density and cover for trees; stem density and cover for shrubs; and cover for herbaceous plants. These abundance data, together with comprehensive locational and landscape data, represent presence and absence data for suitable taxa. These presence-absence data provide opportunities for more robust species distribution and population modelling (Barry & Elith 2006). Guerin and Lowe (2013) used Generalized Additive Modelling (GAM) of ecological site data to produce robust models of species distribution. Presence-absence data is useful to evaluate the predictions of models derived from presence only data (Elith *et al.* 2006).

The survey and mapping program has been focused on the native vegetation, and particularly sites in the best-on-offer condition. However, the survey method requires all plant species to be recorded at a sample site. Hence the program has also greatly increased our knowledge of the distribution of the non-native flora. Table 1 shows that 10.4% (9205) of BRI specimens collected by the QHRESM program are non-native species. Table 2 documents that over 30% of the non-native specimens came through the QHRESM program. Families where the non-native species make a significant proportion of the collections include Solanaceae (33% of QHRESM collections), Asteraceae (28%), Caesalpiniaceae (21%), Amaranthaceae (20%), Malvaceae (20%) and Apocynaceae (17%). Two species of naturalised *Pinus* species and five species of non-native ferns have been collected. The most frequently collected non-native species were *Passiflora suberosa* L. (73 specimens), *Passiflora foetida* L. (72) and *Cynodon dactylon* (L.) Pers. var. *dactylon* (71).

Additionally the CORVEG database contains thousands of records of non-native species that can be used for modelling distribution and populations. As the CORVEG sites are located in the minimally disturbed sites and record quantitative abundance data, they can provide an assessment of impact of non-native species on native vegetation, e.g. percentage of non-native cover which is indicator in the BioCondition assessment method (Eyre *et al.* 2011). CORVEG data can complement specimen data in documenting the spread over time and space of environmental weeds.

Conclusions

Over the past 43 years, the QHRESM program has contributed almost 90000 (89389) specimens to BRI Herbarium accounting for 28% of all specimens added to BRI during this period. These specimens have been collected across all bioregions, pastoral districts and vegetation communities across the state using a systematic sampling approach driven by the requirement to comprehensively sample all vegetation communities. The QHRESM BRI specimens represent more than 79% of the total native and 73% of the naturalised vascular flora of Queensland, and make a valuable contribution to the collections of bryophytes, lichens and liverworts. The data and specimens collected enhance the ability to assess local, state and continental scale plant diversity through improved distribution information and ecological knowledge, and provide material for more comprehensive plant taxonomy at both the morphological and genetic level.

The contribution of the QHRESM program is going to be greater than stated in this paper because the survey and mapping program is not yet completed. Furthermore there is a backlog in getting specimens into BRI for completed projects, and a significant lag in describing new species. In summary the data collected as part of the QHRESM program provides a long term legacy that undoubtedly will be used by botanists, ecologists, governments and the public for long into the future.

Acknowledgements

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