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Quantifying leucaena cultivation extent on grazing land

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Abstract. Leucaena is a perennial fodder crop that can significantly improve beef production across substantial parts of the world's grazing lands. We surveyed leucaena cultivations across 350 000 km^2 of Australia's prime leucaena-growing region, using a new approach to quantify leucaena coverage and distribution. This approach uses high resolution imagery to detect leucaena by the distinctive alley cultivation pattern that is typical in the region and in many other parts of the world. We estimated there are ~123 500 ha of leucaena in the study region. Although no prior estimate of leucaena coverage has been based on exactly the same geographic area, our data strongly suggest that recent published estimates of leucaena coverage for Queensland and Australia are substantial overestimates. In addition to providing robust estimates of total leucaena coverage, we demonstrate how the method can also contribute to other survey objectives such as comparison of actual with potential spatial distribution, and assessment of statistical sampling power. We also discuss the potential application of the new method in international contexts.

Additional keywords: *Leucaena leucocephala*, remote sensing, survey.

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Introduction

Leucaena leucocephala (Lam.) de Wit is a tropical legume, used internationally for a variety of purposes including cattle fodder, nitrogen fixation and firewood (Shelton and Brewbaker 1994). In Australia, and particularly in Queensland, considerable public and private investment has been directed at adoption of leucaena forage systems for the beef industry. In Queensland grazing systems leucaena is typically sown in widely spaced (~4–12 m) rows across native or sown grasslands. This 'alley' pattern of cultivation is common, although not ubiquitous, around the world (Kang and Gutteridge 1994).

A growing body of literature suggests multiple benefits for beef producers from leucaena-grass systems including accelerated liveweight gain in cattle and profitability (Addison *et al*. 1984; Bowen *et al*. 2018), reduced erosion and improved salinity control (Shelton and Dalzell 2007) and reduced greenhouse gas production (Harrison *et al*. 2015). Major challenges faced by users include the cost of establishment and risk of crop failure (Quirk 1994; Shelton and Brewbaker 1994), declining productivity in older crops (Radrizzani *et al*. 2010; Radrizzani *et al*. 2016), and the potential for invasive growth outside cultivated areas (Walton 2003). Leucaena can significantly affect the functioning of both the beef industry and the landscape on which it relies. Consequently, there is great merit in developing methods to efficiently and reliably quantify the extent and distribution of leucaena cultivations in the landscape.

Using remote sensing to quantify the distribution and size of land-cover features including forestry and crops is a mature field of research that has targeted many subjects and used a range of sensors (e.g. Running *et al*. 2004; Lymburner *et al*. 2011; DSITI 2016). Outside of Australia, there seems to be no published estimate of cultivated leucaena extent on grazing lands, although substantial work has focussed on image classification methods for weedy leucaena infestations in Taiwan (Chiou *et al*. 2013; Lu *et al*. 2013). Within Australia, the only published survey of cultivated leucaena (Lesleighter and Shelton 1986) used a mail survey of pastoralists in parts of Queensland, finding 2% of surveyed graziers grew leucaena in 1984, and projecting this number to triple by mid-1986, although the authors did not estimate total area under leucaena cultivation. Other sources largely based on expert knowledge (Table 1), have estimated coverage across varying areas at various times. These estimates highlight two points about leucaena-grass grazing systems in Australia; the rapid expansion since the 1980s, and the preponderance of cultivation in Queensland, particularly central Queensland.

Most of the current spatial data describing the actual distribution of leucaena cultivation in Queensland focuses on

Table 1. Historical estimates of total cultivated leucaena grazing systems in Australia

Source	Estimation date[A]	Estimate (and location)
Wildin (1986)	March 1985	3000 ha (central Queensland) + 1000 ha (other parts of northern Australia)
Wildin (1986)	December 1985	8000 ha (central Queensland)
Wildin (1990)	July 1990	16 000 ha (central Queensland) + 5000 ha (other parts of northern Australia)
Middleton *et al*. (1995)	1995	35 000 ha (northern Australia)
Middleton (1999)	1999	50 000 ha (Queensland)
Walton (2003)	2002	'approaching 100 000' ha (Queensland)
Shelton and Dalzell (2007)	2006	150 000 ha (Queensland)
Shelton and Dalzell (2007)	2017[B]	300 000–500 000 ha (Queensland)

[A]If unspecified in the publication, estimation date is same as publication date.
[B]Forecast estimate.

central Queensland with additional areas in southern Queensland (Shelton and Dalzell 2007). The potential distribution of leucaena is limited by several environmental factors. Among these, leucaena grows best on deep, neutral to alkaline soils of pH >5.5, and in frost-free, higher rainfall (average >600 mm/annum) areas (Cooksley *et al*. 1988; Shelton 1994; Lascano *et al*. 1995; Dalzell *et al*. 2006), though in Australia it is also restricted to areas with <800 mm/annum by its vulnerability to predation by psyllid insects (Bray and Woodroffe 1991; Walton 2003). Published estimates of the total potential leucaena cultivation area, based largely on combinations of the above listed environmental factors, vary widely (Table 2). All estimates to date however suggest that potential growing areas are many times larger than concurrent estimates of actual cultivation area.

This paper documents a simple, yet novel, approach for quantifying the area of rangeland leucaena under cultivation, focusing on Australia's major leucaena-growing region in central and southern Queensland. We surveyed leucaena using high resolution satellite and aerial imagery ($\leq$0.7 m pixel size), identifying cultivations by their distinctive 'alley' pattern, which is typical in the study area. We then trialled the application of this survey method by addressing four questions typically asked of crop and vegetation monitoring data; how much of the study area is under leucaena cultivation, how is leucaena spatially distributed within the study area, how current distribution compares with mapping of potential distribution areas, and how likely the sampling intensity used is to correctly detect future changes in the extent of total cultivation area.

Materials and methods

The study area encompasses four natural resource management regions (Fitzroy Basin Association, Burnett Mary Regional Group, Queensland Murray–Darling Committee and Condamine Alliance) as well as the Western Catchments subregion of the SEQ Catchments natural resource management region, and covers 350 000 km^2 in Queensland, Australia. The entire region has summer-dominant rainfall, long-term (1946–2005) mean rainfall between 1350 mm and 425 mm in the coastal north-east and the south-west respectively, with approximately half the area receiving 600–800 mm of average rainfall per annum (Fig. 1). This area was chosen because it includes the majority of current leucaena cultivation in Queensland and Australia, is a likely area for additional leucaena cultivation, and is covered

Table 2. Estimates of the extent of areas with potential to support leucaena cultivation in Queensland
Predictors are variables used by sources to estimate extent

Source	Estimate	Predictors
Hutton and Gray (1959)	37.3 M ha	Annual rainfall and seasonality, temperature
Middleton *et al.* (1995)	>2 M ha	Land and soil types, 'insect and environment limitations'
Shelton and Dalzell (2007)	13.5 M ha	Soil type and fertility
Peck *et al.* (2011)	8.4 M ha	Land type, soil fertility

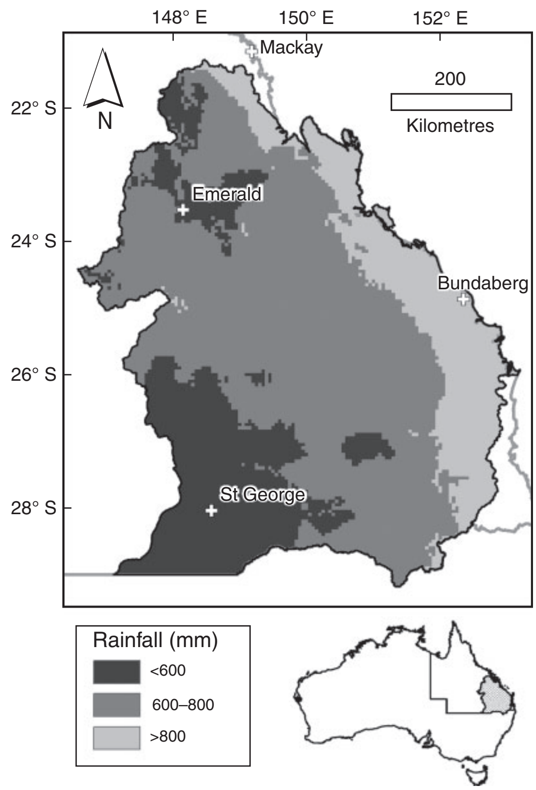

Fig. 1. The study area and its long-term mean annual rainfall (1946–2005), and its position within Queensland and Australia (grey line on main map indicates Queensland border and coastline).

by recent high resolution imagery (DNRM 2016), which was used to visually identify leucaena by its characteristic wide alley cultivation pattern (Fig. 2).

Leucaena was identified by visual inspection of high resolution imagery acquired under the Queensland Spatial Imagery Acquisition Program (DNRM 2016). Image resolution varied from 10 to 70 cm pixel size, and image acquisition dates ranged from 2011 to 2015 inclusive, across the study area (Fig. 3). These images provided >99% coverage of the region, the remaining area being either mountainous, heavily treed country and/or dry (<430 mm/year) inland areas unsuitable for leucaena, and confirmed by assessment of slightly lower resolution imagery (1.5 m pixel size).

The study area was split into a grid of 3 501 859 quadrats 10 ha in area, and 12 561 of these were randomly selected for inclusion in the subsequent survey. As this sample (dataset A) could form the basis for an ongoing monitoring system for leucaena coverage in the region, sampling was deliberately unstratified in relation to any landscape variables to ensure coverage of areas where leucaena is currently absent but which might support leucaena in the future. Dataset A quadrats were overlaid on the imagery, and each quadrat was visually inspected for the presence of leucaena by trained assessors. If a leucaena cultivation pattern was absent from the quadrat, the quadrat was assigned a leucaena coverage value of 0 ha. If leucaena cultivation was observed in the quadrat, one or more polygons were mapped

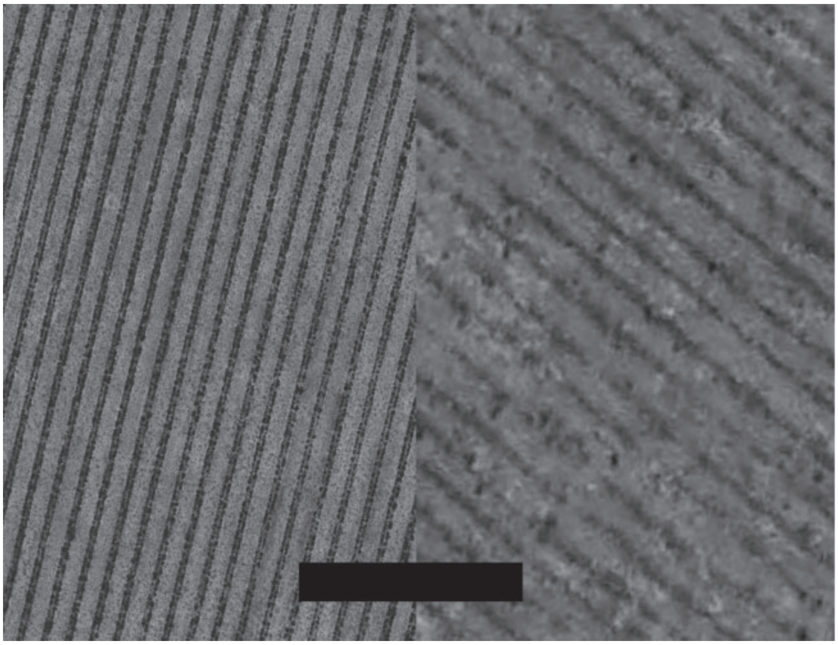

Fig. 2. The distinctive alley cultivation pattern of leucaena viewed in 15 cm (left) and 70 cm (right) pixel imagery. The black bar in the figure indicates 50 m on the ground.

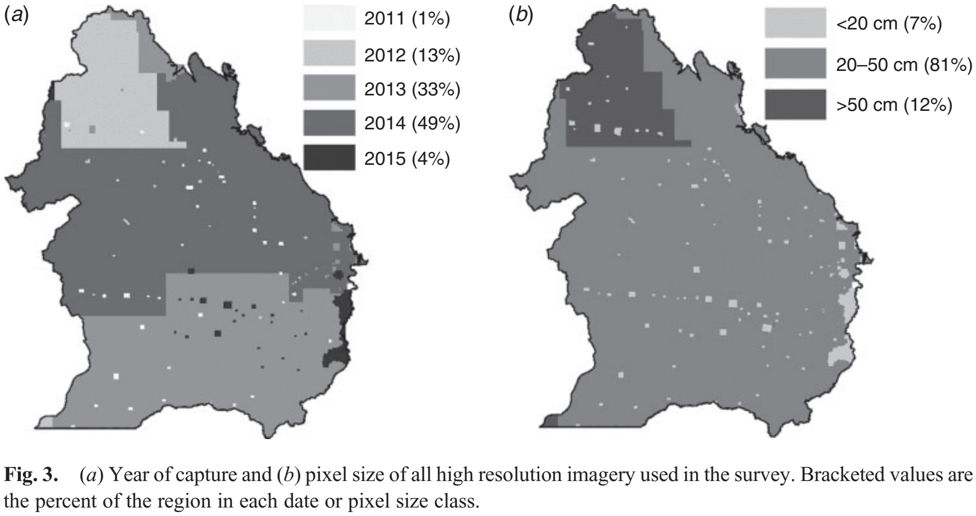

Fig. 3. (*a*) Year of capture and (*b*) pixel size of all high resolution imagery used in the survey. Bracketed values are the percent of the region in each date or pixel size class.

around the quadrat's leucaena cultivation (leucaena rows plus their inter row alleys) using GIS software, and the cultivated leucaena coverage assigned to that quadrat equalled the total hectares within the mapped polygon(s).

A second dataset (dataset B) mapped 105 cadastral land parcels where leucaena was known to be present. The parcels were identified by experienced local advisors and/or during roadside surveys in the study area dating between 2004 and 2011. The dataset B land parcels were overlaid on the high resolution imagery and inspected to test for sampling errors of omission (failures to detect leucaena where it was actually present).

To demonstrate how the image sampling method could also be used to compare actual and potential landscape coverage by leucaena, we mapped three landscape attributes of known significance in leucaena cultivation across the study area, and compared their distribution to that of leucaena mapped in dataset A. The three landscape attributes; long-term average rainfall (<600 mm, 600–800 mm or >800 mm), soil depth (<1 m and >1 m) and soil pH (<5.5 and >5.5) (Viscarra Rossel *et al*. 2015), were used to spatially stratify the landscape into 12 mutually exclusive zones based on their combination of attribute classes. The proportion of dataset A leucaena samples found in each zone was then compared with the proportion of the entire study area in each zone.

Finally, we conducted an analysis to assess the statistical power of the dataset A sample sites to detect temporal change in total regional leucaena cover based on resampling the same sites at a later date. This work involved multiple trials where a second sample of the dataset A was simulated by resampling the original dataset A hectare values. Generation of these second samples was adjusted to simulate different levels of regional leucaena coverage from that seen in the original dataset A sample. The original and second samples were then statistically compared to assess whether the simulated difference in leucaena coverage had been detected. The analysis is explained further below, but is based on the following values, with all areas expressed in hectares:

A1: All 12 561 leucaena hectare values from dataset A;
$\overline{A1}$: Mean of all A1 values;
A2: The 12 561 leucaena hectare values from a simulated resample of A1 sites;
$\overline{A2}$: Mean of all A2 values;
V: The 94 leucaena hectare values >0 recorded in A1 (see Results);
$\overline{V}$: Mean of all V values;
R: The simulated total hectares of leucaena across the survey area at A2;
L: The number of quadrats in A2 with leucaena hectare value >0;
T: 3 501 859 (population of potential sample quadrats in the study area);
H: 123 511 (estimated total hectares of leucaena across survey area at A1 (see Results)).

We selected 30 values of R from across the range H ± 45 000 ha. For each value of R, 10 000 simulations of A2 ($n = 12\,562$) were generated, with each simulation processed as follows.

(1) Initially, let A2 = A1 and $A2_i = A1_i$.
(2) Generate the random binomial L, where P (Success) = P (leucaena present in a sample quadrat, given R) = $(R/T*\overline{V}.)$ and $n = 12\,561$. This defines the number of quadrats in A2 where leucaena hectare value >0.
(3) In simulations where L = 94, maintain $A2_i = A1_i$.
(4) In simulations where L <94, randomly select 94-L quadrats from A2 where $A2_i > 0$, and reassign these as $A2_i = 0$, otherwise maintain $A2_i = A1_i$.
(5) In simulations where L >94, randomly select L-94 values from A2 where $A2_i = 0$, and reassign each with a random sample from V, otherwise maintain $A2_i = A1_i$.
(6) Compare $\overline{A1}$ and $\overline{A2}$ using a two-tailed, paired sample *t*-test.
(7) If sign($\overline{A1}$ – $\overline{A2}$) = sign(H – R) and P(*t*-value) <0.05, the result was classed as correct, as it correctly detected the direction of change in total leucaena coverage between samples A1 and A2.

The sampling power for each value of R was measured as the proportion of the 10 000 simulations where the *t*-test outcome was correct, and thus where the dataset A sample sites were adequate to correctly detect the direction of simulated change in regional leucaena cover.

In the above simulations, the cultivated area of leucaena in the same quadrat of A1 and A2 has three possible trajectories; leucaena cultivation area is unchanged ($A1_i = A2_i$), declines to 0 ($A1_i > 0$ and $A2_i = 0$), or increases from 0 ($A1_i = 0$ and $A2_i > 0$). These trajectories respectively reflect three potential scenarios for change in leucaena cover on a single quadrat; no change in leucaena cultivation area, decline where leucaena is fully removed from the quadrat (e.g. ploughed out, total crop failure), or introduced to a previously uncultivated quadrat. Other change scenarios are also possible, particularly incremental changes like additional cultivation in a quadrat where leucaena is already present or partial decline through frost and insect damage. These were not simulated in this power analysis because A1 is currently our single temporal sample and so provides no quantitative data to inform simulation of incremental change. The power analysis thus covers a substantial, but not exhaustive range of scenarios for change in leucaena coverage on individual quadrats.

Results

Leucaena was detected in only 94 (0.748%) of the dataset A quadrats. The mean area of leucaena per quadrat across all quadrats in dataset A (with 95% confidence intervals) was 0.035 ± 0.009 ha. Multiplying this quadrat coverage by the total population of quadrats in the study area grid (3 501 859) provides an estimate of 123 511 ± 31 210 ha of cultivated leucaena for the entire study area. Figure 4 maps the dataset A sites where leucaena cultivation was detected, and Fig. 5 provides a histogram of the hectares of leucaena mapped in each of these 94 sites.

The land parcels identified in dataset B (where leucaena presence was confirmed before image inspection) were distributed across a similar range to the sites of dataset A where leucaena was detected, and ranged in size from 39 ha to 30 800 ha. Leucaena was successfully detected on 103 (98%) of these land parcels, and we failed to detect cultivated leucaena on only two of the parcels; one with <1 ha of leucaena planted in irregular rows, and another planted in 1986 and since overgrown with other woody vegetation.

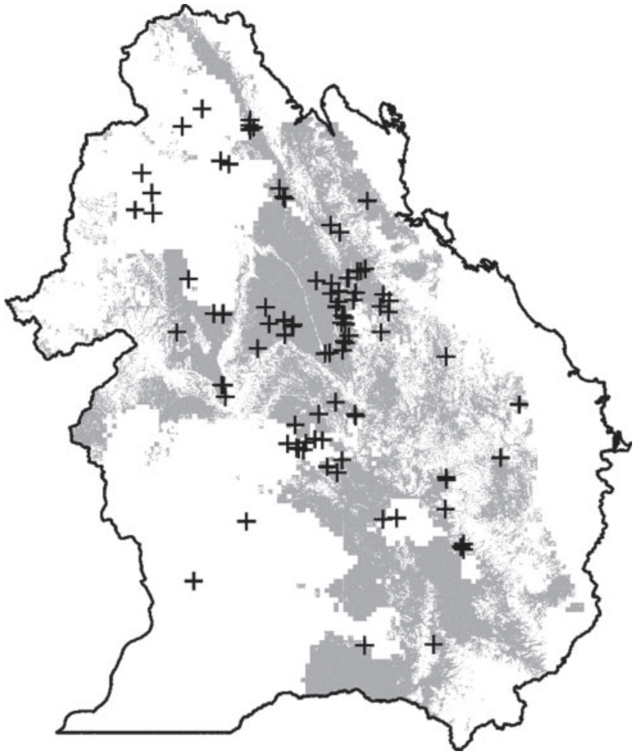

Fig. 4. Dataset A sites where leucaena cultivation was detected ($n = 94$). The background shading indicates areas where soil pH >5.5 and soil depth >1 m and mean average annual rainfall 600–800 mm (as per Table 3).

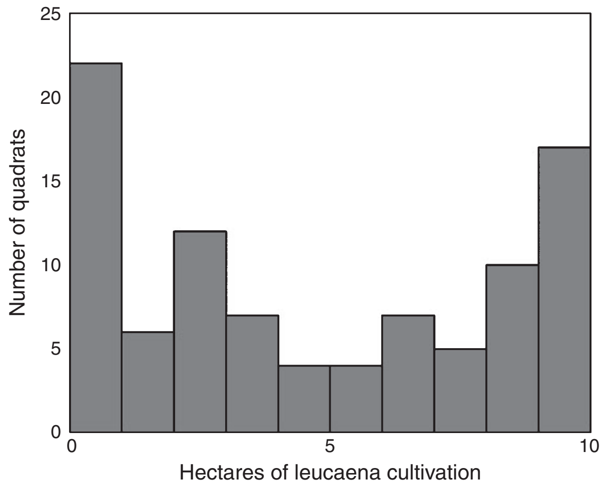

Fig. 5. Distribution of the leucaena hectare values for the 94 dataset A quadrats where leucaena cultivation was detected.

Table 3 compares the respective proportions of the leucaena cultivation mapped in dataset A, and of the study area, in 12 landscape zones. It shows that the three variables used to define these zones (rainfall, soil depth and soil pH) all relate to leucaena distribution. Leucaena cultivation is under represented on shallow soils, with only 1.2% of the leucaena cultivation mapped in dataset A occurring on the 31.6% of the study area on shallow soils. The situation is similar for acidic soils; none of

Table 3. Percentage of mapped leucaena (from dataset A), and of the study area, and total area of the study area, in each of 12 landscape zones defined by mean annual rainfall, soil depth and soil pH ($CaCl_2$ assay at 1–2 m soil depth)

Annual rainfall (mm/year)	Soil depth (m)	Soil pH	Mapped leucaena (%)	Study area (%)	Study area ('000 ha)
<600	<1 m	<5.5	0	0.6	217.8
		>5.5	0.1	6.4	2226.5
	>1 m	<5.5	0	0	9.8
		>5.5	24.4	29.5	10 327.3
600–800	<1 m	<5.5	0	2.3	815.2
		>5.5	1.1	16.8	5872.6
	>1 m	<5.5	0	0.2	85.4
		>5.5	74.4	30.4	10 629.9
>800	<1 m	<5.5	0	3.6	1251.9
		>5.5	0	1.9	654.8
	>1 m	<5.5	0	4.6	1627.7
		>5.5	0	3.7	1299.5

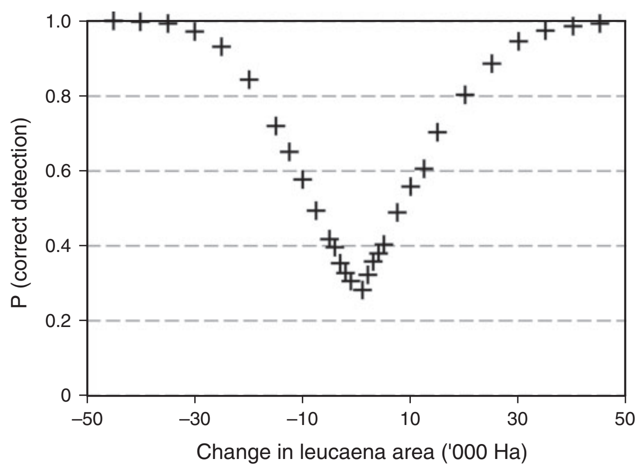

Fig. 6. The sampling power of the dataset A sites at 30 different levels of R. In this graph, R is re-expressed on the *x*-axis as R-H, or the change in regional leucaena cover between sample A1 and simulated sample A2.

the leucaena cultivation mapped in dataset A was detected on very acidic soils despite the fact these soils account for 11.3% of the study area. Leucaena is under-represented in high rainfall zones (no leucaena mapped in dataset A in a zone covering 13.8% of the study area) and to a lesser extent in low rainfall areas (24.5% of mapped leucaena on a zone accounting for 36.5% of the study area). The zone with deep soils of pH >5.5 (using $CaCl_2$ analysis) and 600–800 mm of mean annual rainfall was the only one where leucaena was over-represented, with 74.4% of mapped leucaena cultivations occurring on a zone covering only 30.4% of the study area.

Figure 6 shows the results of the power analysis, indicating the probability that an assessment of future imagery of the dataset A sites would correctly identify the direction of any change in regional leucaena cover. For example, Fig. 6 suggests >55% probability of correctly identifying any change in total leucaena area greater than 10 000 ha, and probabilities of >80% and >94% for changes in total leucaena area greater than 20 000 ha and 30 000 ha respectively.

Discussion

Does image sampling work?

This work demonstrates a simple method to quantify the total area of alley-cultivated leucaena in grazing systems. It relies on detecting the distinct alley pattern seen in leucaena cultivation in the study area, and the availability of suitable high-resolution imagery and GIS software. As alley cultivation is common in international contexts, and imagery and GIS software are increasingly accessible in today's research environment, it seems likely that our method has global applications. Survey personnel can be quickly trained to classify leucaena cultivation in image samples, and any ambiguous samples can be noted and revisited later by more expert assessors, either via the imagery, or in the field if necessary. Additionally, the data can also be used to address a wider suite of survey questions than simply estimating cultivation area, such as mapping regional distribution, and comparing actual and potential distribution.

The methodology also provides scope for ongoing monitoring of rangeland leucaena cultivation, and the same quadrats used here could be revisited as newer imagery becomes available. Sampling from imagery offers several advantages; it can be performed retrospectively, sampling dates are clearly defined by image capture date, and additional samples can be extracted from imagery if statistically required. The power analysis we provided shows that the system should be reasonably sensitive to change in leucaena coverage, another benefit of the quantitative approach that should clarify our ability to track temporal changes in regional leucaena cover. The timing of repeat samples is highly dependent on the availability of updated imagery, but given the growing availability of high resolution imagery, intervals of 5–10 years seem quite feasible.

The use of image sampling also proved suitable to quantitatively compare current leucaena coverage with the distribution of potentially valuable leucaena areas. This capacity has a range of applications including assessing the progress of extension efforts and mitigating financial risk through targeted advice to industry. It should be noted that the landscape attributes we used are not a complete suite of all influences on leucaena cultivation. For example both frost frequency and land tenure conditions influence leucaena cultivation, and a more detailed mapping effort would produce a more nuanced map of potentially suitable areas. For the purposes of this work though, our mapping serves mainly to demonstrate an extension of the sampling method. The insights it provides about the current distribution of leucaena in the study area (discussed below) are an additional, but secondary, outcome of the process.

Findings on abundance and distribution

Although cultivated leucaena varieties were introduced in the study area in the 1960s (Wildin 1981), and its potential economic and ecological impacts on the Queensland beef industry are well known (Walton 2003; Bowen *et al*. 2018), and well promoted (e.g. Dalzell *et al*. 2006; Burgis 2016) there have been limited efforts to quantitatively estimate either the extent or distribution of leucaena cultivations in the area. Our study is the most rigorous analysis so far, and even allowing for different survey areas from previous work, our estimate of 123 500 ha is low when compared with the temporal trajectory of other estimates listed in Table 1. As analyses of dataset B demonstrated that we reliably detected existing leucaena crops, it seems more likely that the most recent estimates of leucaena cultivation area in and around the study area were overestimates. This may be partly attributable to the historical challenges of reliably establishing leucaena (Lesleighter and Shelton 1986; Wildin 1986), in which case planted areas would overestimate mature crop areas. It may also reflect the difficulty of estimating any type of coverage across such a large area without the use of remotely sensed imagery.

Our comparison of potential and actual leucaena distribution found approximately one-quarter of mapped leucaena in suboptimal landscape zones, in particular sites with <600 mm of annual rainfall rather than suboptimal soil characteristics. The reasons for this are not addressed by our results, but as rainfall varies temporally whereas soil depth and pH do not, producers may be more prepared to risk investment in marginal rainfall areas than in marginal soil areas, especially where locations are only slightly below the 600 mm annual rainfall threshold. As expected in the Queensland environment, our results also showed cultivated leucaena is virtually absent in areas with >800 mm of annual rainfall. This reflects several significant challenges to leucaena production in wetter parts of the study area including higher prevalence of psyllid predation and acidic soils with high exchangeable aluminium levels, opportunities for higher value crop production, and higher weed burdens during crop establishment. Recent developments of psyllid resistant leucaena varieties (Dalzell *et al*. 2013) may increase future leucaena coverage in higher rainfall areas, and the methodology we have developed here is worth trialling as a means to monitor the progress of new varieties.

Limitations and implications for future work

This study did not address the staggered timing of the image collection that we used, which similarly staggered our leucaena sampling over 5 years. The only real consequence of this is that our estimate of total leucaena cover cannot be set at a single date, but rather over the temporal span of the sampled imagery. Similar sampling in other parts of the world may also depend on staggered image samples. Like our work, in cases where a one-time measurement is the goal, or where samples are repeated but the imagery used in different samples does not overlap temporally, staggered samples may not present any real statistical issues. However, monitoring studies where imagery is sampled in a progressive fashion as it is captured may need to take the staggering of samples into account to ensure its correct analysis and interpretation.

Our methodology does not provide data on the vigour of the leucaena we detected. Lesleighter and Shelton (1986) highlighted very high levels of crop failure at that time, and more recently Radrizzani *et al*. (2010, 2016) discussed and investigated concerns about declining productivity of leucaena crops in the study area. Certainly, some of the areas we mapped showed patchy leucaena coverage and limited plant height. Whether or not this was indicative of crop failure, rundown, lack of fertiliser, recent pruning, heavy grazing or other unspecified factors is unclear from the single sample we took, though it may become clearer if further imagery is acquired for our sites.

Regardless, it is important to note that our estimate quantifies cultivated leucaena area, but not variations in productivity within that area.

The method we have developed here has two potential limits on its adoption in other regions of the world. First, it is only suitable for large plants cultivated in linear configurations, and is unsuitable where plants and stands are distributed in non-linear patterns. This precludes naturally propagated populations of weedy leucaena, and it is unclear how the method would work where leucaena is interspersed with other tall vegetation. Second, it requires that other local crops (e.g. horticultural tree crops) either have distinctly different row spacing and/or visibly distinct appearance from leucaena during image analysis. These criteria will not be met everywhere leucaena is grown, but the alley pattern of leucaena cultivation is common in some beef producing regions of the world (Kang and Gutteridge 1994). Consequently, the approach has international application, but would need to be evaluated on a regional basis to ensure adequate discrimination of leucaena from other local crops in any image samples.

Conclusion

The paper demonstrates a new approach to rigorously quantify the extent of leucaena-grass systems on grazing lands. Given the documented potential of leucaena to improve beef production and to produce escaped weed populations, it provides a valuable new tool to assess and monitor the extent and distribution of cultivated leucaena in Australia and potentially beyond. Our results also show that estimates since 2002 of leucaena extent, based on expert opinion, were overly optimistic, and the current crop is substantially smaller than previously believed. This information has implications for the beef industry and agencies working to extend and/or monitor leucaena use in the grazing industry.

Conflicts of Interest

The authors declare no conflicts of interest.

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