Executive Summary

Remotely sensed and modelled pasture biomass, land condition and the potential to improve grazing-management decision tools across the Australian rangelands

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Prepared by: Gary Bastin[1], John Carter[2], Philip Tickle[3], Grant Stone[2], Rebecca Trevithick[2], Peter O'Reagain[4], David Phelps[4], Robyn Cowley[5], Matthew Pringle[2], Joe Scanlan[4], Madonna Hoffman[4]

[1] Northern Territory Department of Land Resource Management
[2] Queensland Remote Sensing Centre, Department of Science Information Technology and Innovation.
[3] Cooperative Research Centre for Spatial Information.
[4] Queensland Department of Agriculture and Fisheries (DAF)
[5] Northern Territory Department of Primary Industry and Fisheries (DPIF)

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1 Executive summary

1.1 Introduction

A profitable and environmentally sustainable beef industry is critical to continued productivity and allied socio-economic and cultural well-being in northern Australia. However, recent beef situation analyses conducted for Meat and Livestock Australia rather pessimistically report that most northern beef producers are currently not economically sustainable as they are not able to fund present and future liabilities. Clearly, the current situation must change if the beef industry is to remain viable in this part of Australia. The same analysts (McLean et al. 2014, Holmes 2015) demonstrate that pastoralists have readily adopted technology to increase herd productivity and counteract reduced labour availability. Literacy surrounding management of natural resources has also increased, particularly with regard to the principles and practice of Grazing Land Management and associated delivery programs such as the Grazing Best Management Practices Partnership in Queensland. Thus further relevant technology, including timely, spatially extensive information about resource productivity and condition, can potentially contribute to the efficiency and improved profitability of sustained livestock production in northern Australia.

Important elements of sustainable grazing land management include:

1. Recognition of climate variability,
2. Matching livestock numbers to available forage as seasonally-variable stocking rate, and
3. Adjusting stocking rate within an acceptable tolerance around the realistic long-term safe carrying capacity.

Estimating safe carrying capacity and correct seasonal stocking rate has been assisted by the capacity to model expected pasture growth following variable amounts of rainfall. Allied with this modelling capacity, appropriate analysis of satellite data is increasingly being used to monitor grazing impact upon the rangelands as the check to whether stocking rates and associated grazing management are spatially and temporally appropriate within the range of climate variability that has to be managed.

Essentially, monitoring the dynamics of cover using remote sensing utilizes a two-dimensional view of the vegetated component of the earth's surface. The ability to include the third dimension (height or bulk) to estimate pasture biomass should assist pastoralists in their stock and pasture management. This could operate at two levels: (i) calculated increase in stocking rate in better seasons (based on known forage availability) and (ii) corresponding prudent reduction in stock numbers as forage declines towards threshold levels. An integrated system of modelled and monitored pasture biomass, complemented by adequate ground-truth data, should provide land managers with improved information to better manage their natural resource under continuing climate variability. As of now, we lack the ability and/or resources to accurately and consistently monitor pasture biomass across the diverse rangelands of northern Australia, both directly (i.e. field based) and remotely.

1.2 This report

This report assesses the potential for expanding on current capacity to monitor land condition using remotely-sensed fractional cover products to improve biomass estimation, animal productivity, pasture growth models and grazing decision tools (e.g. safe carrying capacity) across the Australian rangelands. The focus is on northern Australia but includes relevant research and implementation from more intensively grazed parts of southern Australia where appropriate.

The complete report is presented as 2 volumes which include:

1. A review of literature relevant to:
    - Land condition assessment (and monitoring) based on remotely sensed vegetation cover,
    - Remote sensing-based methods for estimating vegetation (including pasture) biomass,
    - Cover-mass relationships that support biomass estimation from remotely sensed ground cover, and
    - Linkages between modelled pasture biomass, safe carrying capacity and land condition.
2. Content from a November 2014 workshop that assembled expert information around (i) the potential for estimating pasture biomass using ground-based, remote sensing and modelling methods, (ii) monitoring land condition by similar means and (iii) calculating safe carrying capacity and appropriate, seasonally-variable, stocking rates.
3. A summary of recent analyses of biomass – cover relationships from grazing trials in northern Australia (Volume 2 by John Carter et al. 2015).
4. Advice on prospective research areas that should allow improved monitoring of pasture biomass and resource condition at paddock scale and larger using a combination of remote sensing and modelling.

1.3 Pasture biomass, safe carrying capacity and land condition

Pasture biomass is the mass (dry weight) of herbage species (pasture) above the ground surface, per unit area (generally, per hectare). This may be of two forms: total standing dry matter (TSDM) or pasture growth for that year (annual growth) or season.

Long-term safe carrying capacity is the number of livestock that an area of land can carry over the long-term (>10 years) without causing a decline in land condition.

Land condition describes the health of grazed rangeland relative to a benchmark or reference area that has been minimally disturbed by past grazing.

1.3.1 Estimating, monitoring and modelling pasture biomass, carrying capacity and land condition

The complete report introduces and reviews methods and Australian experience for each of these components under sub-headings of:

1. Pasture biomass
    - Practical landholder requirements versus the research environment, particularly with regard to information contributed by the Australian Agricultural Company at the November 2014 workshop.
    - Ground-based methods – with particular reference to the BOTANAL technique and its use in recent and ongoing northern grazing trials (Wambiana, Pigeon Hole and Mt Samford).
    - Modelling – with a focus on the GRASP suite (PaddockGRASP, AussieGRASS).

2. Calculating safe carrying capacity as a strategic (long term) requirement for appropriate management of natural resources on pastoral enterprises. Stocking rate is then adjusted, tactically, around the safe carrying capacity based on seasonal availability of forage.

3. Approaches to monitoring and modelling land condition
   - States and transitions, including the ABCD framework included in the Grazing Land Management training module.
   - Monitoring and understanding change and its major drivers, as well as assessing land condition.
   - Experience gained through the Western Australian Rangeland Monitoring System (WARMS) and the Australian Collaborative Rangelands Information System (ACRIS) in partitioning likely causes of change (rainfall, grazing, fire) as they relate to land condition.

1.4 Literature review

The literature review comprises a major part of the report and is difficult to summarise into a few brief statements. The following list of structured sub-headings provides a guide to the contents of the review.

- Remote sensing of land condition
- Remote sensing of biomass
- Modelling pasture biomass
- Modelling land condition
- Data assimilation
- Precision pastoral management tools
- Spatially enabled livestock management

1.5 Northern grazing trials – mass-cover relationships

This section very briefly summarizes the recent work of John Carter and colleagues to predict total standing dry matter (TSDM) from Landsat fractional cover at a range of scales using data from three well measured grazing trials in northern Australia (Wambiana, Pigeon Hole and Toorak). More detail, including example results, is provided in section 4 of the complete report and John Carter and colleagues comprehensively report their results in Volume 2 of this series (Carter et al. 2015).

1.5.1 Main findings

1. Field-based estimates of total ground cover were, in all cases, less than that of the satellite estimate. When the field data were corrected to a point-intercept basis, the cover values for Toorak and Pigeon Hole were quite close.

2. Linear regressions using all data showed that the mass (TSDM) needed for a 1% increase in Landsat-based cover varied with grazing trial. Correcting for apparent bias in estimation at Wambiana produced a similar value to that for Pigeon Hole (~60 kg/ha increase in TSDM per 1% increase in fractional cover). The Toorak data suggested about half of this increase, possibly due to the presence of annual grasses and broad leaved forbs at this grassland site.

   The data for all paddocks at each grazing trial showed that the cover to mass relationship was approximately linear at lower cover values and strongly nonlinear at higher cover values, with clear differences between grazing trials. Non-linear fits to the untransformed data slightly improved correlations.

Data analysis for paddock-by-paddock correlations (as opposed to whole grazing trials) indicated that individual paddocks (treatments) could have different mass-to-cover relationships suggesting that calibration at this scale may provide greater precision.

3. Operational considerations:
   - Data transformation improved model fitting and reduced prediction error. TSDM data were square root transformed, logit transformation was used for percentage-based cover variables and, where TSDM was predicted using two cover variables, correlations were investigated and, where appropriate, a log transformation of the ratio between the two used.
   - Strength of model fitting. There was a very modest fit between satellite ground cover and TSDM where a global function integrating transformed data from all three grazing trials was applied. Prediction errors were large, often 500-1000 kg/ha too high or 500-2000 kg/ha too low, with the Toorak grazing trial having the poorest results. Additionally, predictions for most paddocks were significantly biased.
   - The statistical properties of the data varied between grazing trials. Three statistically different functions were obtained where each grazing trial was treated independently. Using the green component of fractional cover (PV) as a covariate (to total cover, or its converse, bare soil) generally only provided limited improvement in model fitting. This may have been due to most field data being collected in the dry season.

     Adding variables such as the persistent green (woody) component of vegetation cover and an index of pasture growth (the rolling 365-day mean green cover) along with interaction terms significantly improved the estimates of TSDM at each grazing trial. These approaches also reduced error limits some of the time at individual grazing trials and component paddocks. The approach, however, uses many more variables and requires a large data set for robust calibration. It also has the risk that new unique combinations of input variables may generate spurious results. There was a small range of persistent green values making it risky to apply these functions to more woody locations than that present in the calibration data set.
   - The statistical properties of the data also varied among paddocks of individual grazing trials. The model from one paddock generally performed poorly in predicting TSDM (from Landsat-based fractional cover) for other paddocks. RMSE values for transformed data indicated a significant decline in skill relative to using all data from the grazing trial. This test is probably a reasonable assessment of field performance on "independent" data as one would expect a decline in predictive skill if the best equations were used at new locations.
   - Calibrating models for one point in time generally resulted in their limited performance over time. This was partly due to limited available data at individual dates (or years) – just six values in the case of Toorak. Inter-annual variability in rainfall tends to have an overriding effect which can be much larger than treatment (paddock-to-paddock) differences.
   - Model performance, in terms of predicting TSDM, did not appear to be improved by calibrating for individual land types within paddocks. This test was conducted using the Wambiana data which had been collected across three land types of approximately equal area in each of the ten trial paddocks.

- Green cover is likely to provide greater insight into model performance and be of greater use in parameter adjustment than dry cover as the former is closely connected with pasture growth while total and dry cover are the result of growth plus the additional processes of detachment, grazing, litter formation and litter decay. The remotely-sensed green fraction of ground cover (PV) was compared to simulated green cover from the GRASP model for a number of paddocks at Wambiana. Initial model runs suggested that GRASP green (PV) cover estimates were on average slightly lower than satellite estimates in average and dry years, and too high in the six wettest years. In 2007, estimates were quite poor and much lower than satellite estimates for unknown reasons.
- There may be potential for the green (PV) fraction of Landsat ground cover to better calibrate GRASP simulation of green cover.

1.5.2 Recommendations

Based on their work, John Carter and colleagues proposed a number of next-steps to develop generalized relationships between Landsat fractional cover and field-estimated TSDM (see Volume 2. Carter et al. 2015 for the complete list). Most of their recommendations are included in the general suite of proposed further work in Section 1.8.2.2.

1.6 Safe livestock carrying capacity

Content in this section is based on the accumulated experience and synthesized knowledge of rangeland scientists who have used the GRASP suite of models (particularly PaddockGRASP) across a wide cross-section of northern Australia to advise pastoralists on safe carrying capacity.

Important considerations in calculating and using safe carrying capacity include:

1. Land type and condition.
   - Currently, the GRASP model is parameterized for the more common, productive land types and its use should be restricted to such. “Land type” depends on definition and the user should check that their intended application matches the described land type that the model has been parameterized for. Extrapolation or expert local knowledge should be used for non-described land types where it is not appropriate to apply the model.
   - Current capability allows modelling of a range of tree covers (for parameterized land types). Pasture growth is simulated for land in ‘A’ condition with percentage discounts then applied for land in lesser condition (B, C or D).
2. Additional factors to consider in translating livestock carrying capacity to actual carrying capacity (stocking rate) include:
   - The period involved (weeks, months, >1 year).
   - Safe levels of pasture utilisation without degrading pastures.
   - Appropriately accounting for paddock characteristics (the area over which the calculated carrying capacity is being applied) – e.g. distance from water and other factors influencing accessibility by livestock.

1.7 Synthesis

Pastoralists need reliable and timely information on forage availability in order to adjust the number of livestock in each paddock for current seasonal conditions. This should be a periodic, conscious (tactical) decision based on a calculated, strategic, safe carrying capacity. Seasonal grazing pressure should also take account of current land condition. The three components are linked (Fig. 1.1): getting the seasonal stocking rate right can improve land condition over time (provided a threshold of degradation has not been crossed) which, in turn, can increase the safe carrying capacity, based on current land condition. In reverse, prolonged excessive stocking variously degrades landscapes, depending on their inherent stability and resilience, which erodes long-term safe carrying capacity.

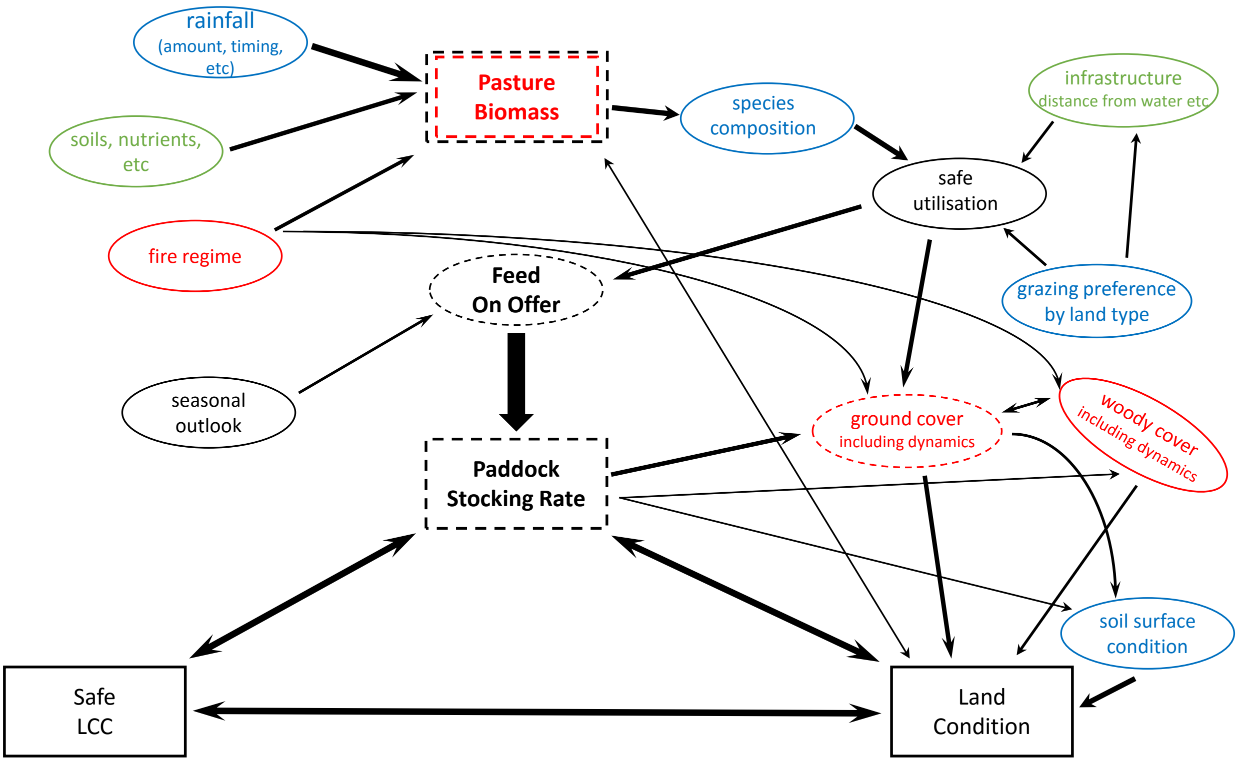

Figure 1-1. Stylized representation of the inter-related components determining paddock stocking rate and land condition. Components within boxes or ellipses with dashed lines represent 'fast' variables and are more commonly associated with tactical decision making. Corresponding shapes with solid lines indicate slower variables and strategic decisions. Blue text and shapes indicate essentially ground-based data, red font and lines are associated with remote sensing, green colouring shows GIS layers and black text / shapes describe mainly modelling components.

1.7.1 What is needed where?

In the simplest sense, paddock stocking rate is dependent on the seasonal supply of palatable and usable forage. This parameter is a function of pasture species composition (i.e. palatability), grazing preference (land type) and acceptable levels of pasture utilisation. It is important to recognize that providing modelled and/or remotely monitored estimates of pasture biomass is the first step; the value of this attribute for setting (and adjusting) paddock stocking rate then needs to be modified by those paddock-specific factors that influence the actual safe level of forage available for grazing.

Making the correct tactical decision on paddock stocking rate, year in – year out, within the broader context of long-term safe carrying capacity, current land condition and often high inter-annual variability in rainfall determines management effects on land condition, longer-term profitability and, regionally, longer term sustainability of pastoralism as a land use.

Requirements for improved delivery of information that will assist grazing land management include:

1. An objective basis for setting stocking rate at critical decision points based on available pasture, determined from remote sensing and well-calibrated models. Contributing components include:
   - Existing ground data (and particularly that obtained from grazing trials), targeted further collections through dedicated calibration / validation exercises and, potentially, crowd-sourced validation data provided by participating pastoralists and others.
   - Proximal and airborne LiDAR to provide proxy data on sward height and vertical structure. Radar data may contribute useful additional information, particularly where cloud is an issue in the tropics.
   - Expanded research on the utility of radar backscatter at various wavelengths for directly calibrating pasture biomass.
   - Other forms of optical (passive) remote sensing including defining the grassland boundary and associated environmental conditions, particularly climate, over which time-integrated NDVI may reliably indicate pasture biomass.
   - Integrating remote sensing and modelling approaches through data assimilation such as that being developed in the C-Store research project.
   - Knowledge of the error associated with such estimates; whether derived from ground-based assessment, remotely monitored, modelled or a combination of all methods.

2. Pastoralists should have sufficient quantitative information to clearly understand the effects of their grazing management on ground cover dynamics. This includes historic levels of ground cover at critical decision points. Tools are required to effectively detrend the seasonal (mainly rainfall) component of inter-annual change in ground cover and account for fire effects where necessary.

3. Widespread use of modelled carrying capacity coupled with paddock-level changes in land condition (from seasonally-detrended changes in ground-cover) as fundamental components for longer term property development and management.

Essentially then, the “what” is *up-scaled and remotely estimated (and monitored) pasture biomass for improved setting of short term (seasonal) stocking rate in each paddock*, with due regard to the calculated long-term safe carrying capacity, and such that land condition is maintained or improved. Providing this information in a timely manner should assist improved grazing management, including land condition.

The “where” is considered to be all pastoral properties but a tractable starting point probably should be the pastorally more productive bioregions in northern Australia.

1.7.2 Pasture biomass in reality

There are three broadly based approaches to estimating pasture biomass at paddock scale in the rangelands: ground-based, remote sensing and modelling (Fig. 1-2). Each has its strengths and weaknesses. A fourth generic approach, data assimilation, integrates or builds on the strengths of each.

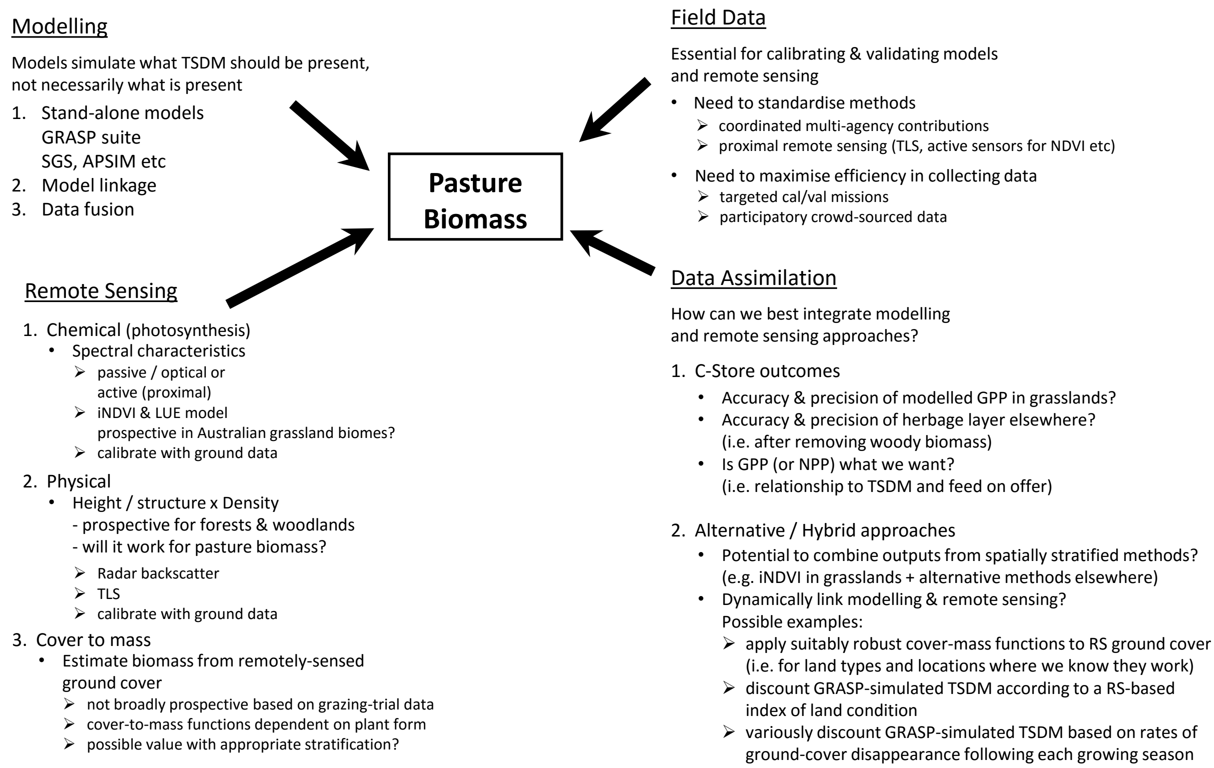

Figure 1-2. Summary categorization of approaches to estimating pasture biomass at paddock scale in the rangelands.

Further information about, and justification for, the above requirements is provided in the following "roadmap" (with more information in the corresponding section of the complete report).

1.8 Roadmap for improved monitoring of pasture biomass

Appropriate field data are essential for calibrating and validating remote sensing and modelling approaches. However, currently used methods are not viable for up-scaling to the larger and more heterogeneous paddocks of commercial grazing enterprises because of the sampling intensity required to obtain sufficiently reliable, spatially-integrated estimates of pasture biomass. Many assessments are required across the range of land types present in larger paddocks to have some confidence in the resultant paddock-scale estimate of pasture biomass. Using timely remotely sensed fractional cover products has the potential to significantly improve field sampling efficiency. Stratifying paddocks in terms of land type and low-medium-high cover levels is likely to significantly improve sampling efficiency and pasture budgeting.

Grazing systems in some parts of Australia have well developed models for simulating pasture growth and TSDM based on rainfall and soil type (as a proxy for water and nutrient availability). The GRASP suite has been applied in different parts of northern Australia and the SGS model, developed for more intensively grazed pastures in the higher rainfall areas of southern Australia, is now being evaluated in the rangelands where suitable datasets exist (the Wambiana grazing trial at this stage).

The ability to simulate pasture growth in a variable climate assists the calculation of long-term safe carrying capacity. Further, GRASP allows the effects of grazing strategy, including stocking rate, on land condition to be investigated based on a simple function between simulated pasture utilisation and the probable presence of perennial grasses. This modelling capacity provides a powerful toolset for investigating 'what if' scenarios. However, at the end of the day, most models predict what should happen and this may not necessarily agree with what did happen (or is happening). Including dynamic components such as remotely sensed estimates of pasture biomass at key times and independently assessed land condition (perhaps based on remotely sensed ground-cover dynamics) may increase the functionality of existing modelling approaches. If this is sensible, then it suggests a data assimilation methodology that effectively harnesses the strengths of remote sensing and modelling.

The following sections summarise key points and recommendations for the further development of an integrated approach to reliably estimating pasture biomass at paddock scale.

1.8.1 Field based estimation of biomass and utilisation

Recommendations include:

1. Develop and apply nationally consistent, standardized methods / protocols for collecting site-based biomass data for remote sensing purposes. This could be through a suitably adapted form of the methodology used to collect field data for calibrating and validating remotely sensed fractional vegetation cover (Muir et al. 2011).

2. Develop appropriate protocols for adequately dealing with spatial heterogeneity of vegetation, at varying scales, as part of further biomass sampling. Technical issues include:
   - Landscape stratification. The recently released Soil Landscape Grid of Australia (at 90 m resolution) should provide useful contextual information with regard to spatial variation in soils to assist sampling design.
   - Determining whether heterogeneity is relatively constant or variable across the area to be sampled, and beyond. Remotely sensed data can assist here – e.g. examining the variance (texture) of cover components at increasing spatial scale. Using timely remotely-sensed fractional cover products has the potential to significantly improve field sampling efficiency. Stratifying paddocks in terms of land type and low-medium-high cover levels is likely to significantly improve sampling efficiency and pasture budgeting. Care is required not to confound subsequent data analyses where the same dataset is used for two different purposes. This can occur, for example, where Landsat fractional cover is included as a stratification layer to assist sampling design and then subsequently used to investigate grazing effects.
   - Allied with the above, ensuring good operator calibration for field-based estimation of cover and biomass including specifying acceptable levels of precision for each data type collected. In short, what is the tolerance around the standard error of plot-level mean cover and biomass for the acquired data to remain useful?

3. Build on existing agency-based extension programs and national initiatives to facilitate the collection of further biomass data for calibration and validation purposes. For example:
   - There may be potential to leverage off the Grazing Land Management program and its more recent derivatives to increase the geographic range and quantity of contributed field-based biomass data. A critical issue from such an approach will be data quality –

which, potentially, can be managed through the application of a national standard (flagged above).

- Influence the TERN AusPlots rangelands program to include plot-based estimates of pasture biomass when collecting biodiversity and cover information. Note that continued funding of the TERN facility and its AusPlots component is uncertain and this option, if successful, may only provide short-term expediency.

4. Use existing field stations (e.g. Spyglass, Brian Pastures, Kidman Springs) to provide integrated field measurement programs that address knowledge gaps for remote sensing and modelling.

5. Crowd-sourced estimates of pasture biomass could be an asset, perhaps more so for validating biomass products derived from remote sensing (as distinct from their calibration). Again, data quality is an important issue to be managed.

   One immediate prospect here is collaborating with pastoral companies that already monitor paddock-level forage availability for setting seasonal stocking rates and planning turn-off, including inter-property transfers of livestock. Gerard Davis, AACo General Manager, Technology & Innovation, indicated at the November 2014 workshop that such contributions are possible provided their data are not considered commercial-in-confidence.

   A critical allied consideration is the ethical use and representation of such data by the scientific community. Voluntarily contributed data, where fit for purpose, should be highly valued and the contributors duly acknowledged as part of scientific communication. The Data Object Identifier (DOI) is a suitable mechanism for duly recognizing third-party scientific data but this may not extend to less rigorous, crowd-sourced data that is nevertheless contributed in good faith.

6. Include relevant proximal (ground-based) remote sensing technologies in future dedicated programs to collect calibration and validation data for modelling and remotely sensing pasture biomass. Actual equipment used and data acquired are, of course, dependent on intended purpose but possibilities include:
   - Active sensing of photosynthetic activity in the red – near infrared wavelengths (to compute NDVI). Use of near-ground active sensing apparently enhances signal to noise data quality, compared with passive sensing of reflected solar radiation where shadow, cloud, time of day and time of year variously affect NDVI separate to photosynthesis (David Lamb, pers comm.).
   - Terrestrial laser scanning to potentially provide proxies for pasture height and sward structure.

7. Facilitate data collation from former grazing trials (and other sources) that have potential value for validating modelled and/or remotely sensed estimates of pasture biomass based on archived satellite data. This will expand on data from the tier 1 grazing-trial sites (Wambiana, Toorak and Pigeon Hole) analysed by Carter et al. (2015) for this report. Tier 2 sites have been identified and there is an informal list of potential tier 3 sites (the suitability of data for modelling purposes is presumed to decline from tier 1 to tier 3). Further activity could include:
   - Formally specifying and documenting the criteria for each tier (akin to gold, silver and bronze standards) followed by the ranking of known datasets based on their suitability against the criteria.

- Capturing required GIS data for historical grazing trials to enable spatial analysis such as that conducted for tier 1 sites.
- Making contact with the data custodians (including data originators where possible) and providing necessary assistance to include all data (particularly textual / descriptive information) in a suitably structured database. A useful guide here, in terms of likely resourcing, is the process recently used to submit data from the Queensland brigalow grazing trials to the TERN EcoInformatics facility.

1.8.2 Remotely sensed biomass

Remote sensing-based recommendations are grouped into three categories: time-integrated NDVI as a spectral (chemistry-based) index of photosynthetic activity and biomass accumulation; a physical (volumetric and density) based approach to estimating biomass using radar and laser scanning; and limited further work on cover-to-mass relationships to evaluate their feasibility for estimating biomass from Landsat-derived ground cover.

1.8.2.1 Time-integrated NDVI

1. Test if pasture growth measured at various "Gunsynd / Swiftsynd" sites can be estimated from an "area under the NDVI or green cover curve" methodology using Landsat and/or MODIS satellite imagery.

2. Specify where and how time-integrated NDVI (iNDVI) through semi-regular growing seasons may contribute to remotely monitored pasture biomass in the Australian rangelands.

   Geographically, the intuitive starting point would seem to be grasslands of northern Australia with reasonably reliable summer rainfall. If this is valid, then systematic field-based estimation of green pasture biomass is required in this biome (or component bioregions) to develop robust models between iNDVI (probably initially derived from the relatively frequent coverage provided by the 250-m MODIS product) and available field data. The CRCSI and partners' work in the West Kimberly, and David Phelp's recent work in the Mitchell Grass Downs has demonstrated potential which needs to be validated in other biomes.

3. Beyond the foundational research required above, the potential geographic range of the method and the environmental conditions within which it is suitably robust need to be defined. Anticipated limitations to the widespread application of iNDVI include:
   - Highly variable, episodic or counter-seasonal rainfall meaning the lack of a sufficiently defined growing season in many rangeland regions.
   - Green trees and shrubs contributing to remotely-sensed photosynthetic activity, thereby weakening statistical relationships between NDVI and green pasture biomass. There is some capacity to spatially mask the NDVI contribution of woody vegetation, e.g. by using the Landsat persistent green product. The ability to do so probably declines in open woodlands and shrublands where woody FPC is quite low but yet may contribute significantly to any satellite-sensed NDVI signal when the pasture is mostly senescent.
   - While the prospects for remotely sensing green pasture biomass using iNDVI in some grasslands would seem to be encouraging, the challenge remains to reliably estimate TSDM, as distinct from green biomass, where the NDVI signal is diluted due to mixed green and dry pasture. This will likely be the case where:

- There is abundant dry feed throughout the growing season;
  - The growing season is poor, i.e. limited and/or patchy rainfall; or
  - There is a high stocking rate such that livestock consume most of the green pick through the growing season.

- A further complicating factor is the interaction between the NDVI signal and land condition. For example, the flush of ephemeral forbs, grasses and other weedy species present on degraded land following rainfall will generate high NDVI values and may give the illusion of good ground cover and biomass accumulation when, in effect, both attributes return to low values as the growth quickly matures and then decays. It may be that this problem can really only be overcome by knowing, a priori, what the land condition is and applying a different function to model biomass from iNDVI.

4. It may be possible to assess the spatial and temporal constraints to the feasibility of iNDVI in the absence of systematic field data, e.g. through a 'desk top' analysis of spatially stratified rainfall characteristics (seasonality, reliability, effectiveness for pasture growth, etc), archived NDVI imagery of suitable temporal frequency and spatial resolution (probably MODIS, but only since late 2000) and other GIS layers (woody FPC, land system mapping, etc).

At this stage, iNDVI in grasslands through reasonably well-defined growing seasons appears prospective for remotely monitoring pasture biomass. This is based on a wealth of international literature (examples identified in the literature review), the Pastures from Space program in south west WA, and current WA Landgate and CRCSI research in the Kimberley (Liveringa Station) and the Queensland Mitchell grasslands (David Phelps). There is a need to systematically define the probable geographic extent and associated climatic and other environmental conditions in the rangelands where this method is prospective and then acquire the necessary field data to develop suitably robust models between NDVI and (green) pasture biomass.

1.8.2.2 Cover – mass relationships

There appears to be limited scope for deriving and applying generalized robust cover – mass relationships such that TSDM can be predicted from Landsat-based ground cover across extensive and diverse landscapes (Carter et al. 2015). However to confirm this, these authors recommend some additional investigation of this modelling approach. Their recommendations specific to remotely sensed ground cover include:

1. Assemble fine scale data from Pigeon Hole and test if calibration can be improved.
2. Improve fractional cover calibrations for locations with bright soils using the Wambiana data as one of the test locations. Current experience is that bare soil is under estimated and the fraction of non-photosynthetic vegetation over estimated for some bright soils. Additional measurement of the fractional cover components on bright soils is required throughout the rangelands to achieve this improved calibration.
3. Identify the causes of occasional spikes and dropouts in the Landsat fractional cover archive. This 'house keeping' measure should add a further quality flag to the archived fractional cover data and improve efficiency in selecting suitable data for statistical analysis.

4. Evaluate if a rolling average, median or medoid[1] of fractional cover over a specified time period is superior to single-date data. Carter et al. (2015) selected archived image dates which were closest to the dates of field data collection. A flexible selection process may improve statistical relationships between field-estimated TSDM and remotely sensed ground-cover.

   In a similar manner, investigate variants of the “average 365 days of green cover” used for current modelling (e.g. add 24, 18, 6 and 3 months as additional independent variables).
5. Investigate if tree-canopy removing fires could be included in a variant of the persistent green cover product to improve ground cover estimates.
6. Improve the current data extraction system to supply data at points (e.g. 3x3 pixels) for additional analysis. Currently, data are extracted for paddocks (i.e. polygons). Modelling of cover – mass relationships may be improved by better controlling spatial variability (i.e. averaging across small groups of pixels rather than paddocks). However this is counter to the aim of developing generically robust relationships that accommodate acceptable levels of variability.

   Similarly, improve the data extraction procedure to cope with east-west (Landsat) scene boundaries.
7. Use data from tier 2 grazing trials to conduct a fully spatially independent evaluation of parameters for TSDM estimation selected from the “best matched” of the three calibrated tier-1 grazing trials and any future satellite-to-biomass models developed.

8. Assess the level of precision needed to allow useful modelling, including the importance of asymmetric error (i.e. large errors in predicted TSDM at close to 100% cover and reduced errors at lower cover values, i.e. the functions cannot return negative TSDM at low cover). This will help determine whether the current 95% prediction limits provide useful information.
9. Assess the level of accuracy required to provide better estimates of TSDM than are currently being used by the grazing industry. For example, the large errors (often under-estimates) at high biomass and cover levels may not be a limiting factor. Would information derived from prediction limits be useful? For example, “there is a 95% chance that TSDM is somewhere between 0 kg/ha and 950 kg/ha”.

1.8.2.3 Sward structure and radar

There are encouraging early results to demonstrate statistical relationships between radar backscatter and pasture biomass (Fig. 3-9 of the main report), sufficient to support the argument for further systematic research in this area. However, it is highly unlikely that a small set of simple universal functions will apply and it is probable that various forms of stratification will be required to develop suitably robust relationships across diverse landscapes. Scientists in the Joint Remote Sensing Research Program have shown how multivariate analysis of combined GIS and remotely sensed data sets can provide novel forms of stratification to assist biomass estimation in forests. These methods, suitably adapted, may be transferrable to the rangelands.

[1] The medoid is a multi-dimensional median. It is used as a way of compositing multi-temporal satellite images over a season (or other time period) to reduce contamination by cloud and other problems (e.g. sensor malfunction). Seasons here are summer, autumn, winter and spring.

Research areas include:

1. Systematic evaluation of the various forms and wavelengths of radar backscatter to determine the most prospective approaches to remotely estimating pasture biomass.

2. As supplementary research to the preceding, investigate the potential for, and best approaches to, landscape stratification to increase the value of preliminary large-area evaluation of radar imagery for biomass estimation.

3. Systematically estimate site-based pasture biomass across pastorally productive (bio) regions in the rangelands to provide comprehensive field data for calibrating and validating the most prospective forms of radar backscatter. This should be a nationally sponsored and coordinated effort, similar in many respects to the recent campaign to collect fractional vegetation cover for calibrating MODIS and Landsat data (Muir et al. 2011). As per recommendation 1 in section 1.8.1, a nationally consistent, standardized protocol is required at the outset to collect suitable biomass data.

4. Terrestrial laser scanning (TLS) has shown considerable potential to rapidly characterize the structure of woodlands and forests. Its value for similarly characterising sward structure in pastures, and the value of this proxy volumetric information for improving radar-based biomass estimation, should be determined – again, across diverse sward structures (tussock grasses, bunch grasses, stoloniferous mat-forming grasses, etc). If TLS data do provide additional value for modelling pasture biomass, then include its routine use in the national campaign to acquire field data on pasture biomass, again using an agreed standardized protocol.

1.8.3 Modelled biomass and derived value

Recommendations for improved modelling of pasture biomass centre on model improvement per se, possible synergies to be gained from linking models (or appropriate sub-models) and data fusion.

1. Carter et al. (2015) provide specific recommendations for improving parts of the GRASP suite (reproduced in section 4.3 of the main report). These are mainly technical 'in-house' issues for Queensland Government staff to implement but some of the more complex requirements may require external support.
    - Include remotely-sensed fractional cover as an additional management-record data-type to expand current GRASP functionality.
    - In a new version of GRASP, replace the runoff cover function with the function used for green cover. GRASP has separate arithmetic functions for transforming actively growing (green) and total biomass to cover. The green-cover function is used to calculate green cover for transpiration and interception of solar radiation while the total-cover function is used to calculate ground cover for estimating erosion risk. It is likely that the 'green cover' function is suitable for both purposes (as is the case in AussieGRASS).
    - Implement a cover algorithm that accounts for layered cover and litter.

      Modelling where satellite cover data are used in calibration / validation may require modifications to parameters to reflect the differences between quadrat-based and point-intercept based measures of cover. The way in which cover is measured (or estimated) matters for calibrating models: separate research has shown that quadrat-based estimates differ from point-intercept measurement.

- Future modelling at paddock and property scale should utilise available remotely sensed products for validation and possible calibration with due regard to the field method used to estimate cover and model parameters.

2. There may be further scope to test the complementarity of existing models in environments external to where they were developed and applied. This has been demonstrated with the SGS model using the Wambiana dataset. Further gains may be small and incremental here as there are likely few rangeland datasets beyond the tier 1 set analysed by Carter et al. (2015) that provide the quantity and quality of data required to adequately parameterize, and then effectively test, the performance of alternative pasture growth models. There are probable additional overheads in (i) adapting the software to suitably simulate pasture growth in different rangeland environments and (ii) reformatting calibration datasets to the requirements of alternative models.

3. The power of linking models is well demonstrated, e.g. using simulated pasture growth as input to animal production models and then passing that output to economic models; examples in Scanlan et al. (2014) and Doran-Browne et al. (2014), and is a purpose-built feature of the SGS modelling suite. Such bio-economic modelling goes beyond the possible benefits to be gained through model linkage for improved simulation of pasture biomass.

- Applying the functionally of the most appropriate components (sub-models) of broadly different models (GRASP, SGS, GrassGro, APSIM etc) may enhance our ability to reliably simulate pasture growth and derived secondary production over larger areas. The way in which this is done should be directed by what parts of available models best meet specified requirements. This could include, for example:
- A feed budget calculator that combines simulated pasture biomass with information on species composition (either modelled, inferred or available externally), grazing preference, distance from water, type and class of livestock, etc (i.e. components in the top right of Fig. 1-1) to calculate paddock stocking rate for defined periods.
- Modelled livestock performance, particularly growth rate, based on simulated forage availability (as above) and dynamic accounting for pasture quality, e.g. based on periodic near-infrared spectroscopy (NIRS) of fecal samples.

4. There are potential benefits to be gained in the modelling sphere based on data fusion[2]. An obvious example is the further inclusion of remotely sensed data and the derived information these data provide, acknowledging that this already occurs in many models (e.g. use of NDVI in GRASP). As a broad distinction, remote sensing quantifies stocks or pools while models simulate flows or transfers among pools.

   Including information on remotely sensed trends in the woody and herbage components of cover as dynamic input variables to modelled pasture growth would seem to be one sensible application of data fusion. This is flagged above for the GRASP model (section 1.8.3). There may be broader potential to include dynamic components of cover in other models.

[2] Data fusion is the process of integration of multiple data and knowledge representing the same real-world object into a consistent, accurate, and useful representation (Wikipedia, accessed 25 June 2015).

1.8.4 Data assimilation

1.8.4.1 C-Store

The C-Store modelling approach of Randall Donohue and colleagues in CSIRO appeals as an integrated, nationally consistent method for modelling gross primary production (GPP). It is attractive because it uses a relatively simple, but internationally recognized, diffuse modelling approach to estimate GPP based largely on remotely-sensed interception of sunlight by photosynthesizing vegetation. Modelled GPP is adjusted for respiration to calculate net primary production (NPP) which is then partitioned into the woody and leaf fractions, termed the carbon store. This modelled output is then combined with available field data (the assimilation process) to refine the modelled components of NPP. Importantly, the output includes calculated error surfaces for each NPP pool. Understanding the source and magnitude of errors initially assists diagnostic improvement of model components and, when this process is optimized, provides a sound rationale for evaluating the accuracy and precision of modelled output.

Criteria for evaluating whether C-Store adequately simulates pasture biomass nationally include:

- What is the accuracy of modelled grass-leaf biomass across the range of pastorally important rangeland (bio)regions? This question is based on the premise that, nationally, C-Store is required to suitably model all carbon pools across diverse biomes (forests to sparsely vegetated deserts) which, of course, covers a very large range of biomass. The grass-leaf pool (per unit area) also encompasses a large range; just in the rangelands, from tropical tall-grass savanna to arid short-grass pastures. Can C-Store be adequately calibrated to suitably perform, within all carbon pools, across these large ranges of NPP?
- How well can grass-leaf biomass be transformed to our more conventional (or familiar) modelling of pasture biomass, i.e. TSDM, green biomass, etc?
- Are there sufficient field data to suitably model GPP and derived grass-leaf biomass across pastorally productive (bio)regions? This should be apparent from the magnitude of mapped errors and should assist in prioritizing acquisition of further field data.
- Is the spatial resolution and temporal frequency of modelled output adequate to assist paddock-scale management? As an initial product for evaluation, the 250-m pixel size and monthly time step of C-Store output certainly seem attractive.

The above criteria, to the extent that they are sensible, suggest the following recommendations towards achieving a national C-Store produced pasture-biomass product:

1. Systematically evaluate C-Store output as it becomes available for its efficiency in reliably modelling grass-leaf biomass in the pastorally important (bio) regions of Australia.

2. If necessary, develop quantitative relationships between C-Store modelled grass-leaf biomass and other forms of modelled and estimated biomass (TSDM, green growth, etc).

3. Based on evaluation of the error surfaces generated by C-Store, contribute to a nationally coordinated program to collect targeted field-based biomass data to improve model performance.

4. If necessary (based on the preceding evaluation), consider developing a variant (or sub-model) of C-Store which focuses on improved simulation of the grass-leaf pool to better

simulate pasture biomass. Excluding the present modelling of other pools may be less constraining in suitably parameterizing and calibrating a herbage-specific variant (or sub-model).

1.8.4.2 Other data assimilation possibilities

1. Investigate potential benefits to be gained from including land condition, based on remotely sensed ground-cover dynamics, as an input to simulated pasture growth and TSDM by such models as GRASP. At present, land condition (in GRASP) is predicted based on the theoretical relationship between perennial-grass composition and pasture utilisation (McKeon et al. 2000). Including actual land condition as a dynamic input variable may improve the accuracy in predicting pasture growth and TSDM, over the current method, for different condition states.

2. Other possibilities of the data-assimilation approach (or, at least, hybrid approaches) are suggested in Fig. 1-2 but we are not yet able to provide firm recommendations for their development. The plausibility of the following suggestions should become clearer as knowledge and capability develops through the C-Store experience.
   - Investigate the value to be gained from using spatially stratified methods that apply the regionally best combinations of modelling, remote sensing and available field data. This represents an optimization approach rather than trying to develop a 'one size fits all' method to biomass estimation in the grazed rangelands. A starting point could be the use of time-integrated NDVI in extensive grasslands that have a semi-regular growing season (section 1.8.2.1) and estimating pasture biomass from remotely sensed ground cover in other areas where mass-to-cover relationships are suitably robust (section 1.8.2.2).
   - Include feedback loops in models of pasture growth that account for spatially and temporally variable rates of pasture biomass depletion (including consumption and trampling by livestock) following significant growth events. This may require the use of high temporal-frequency remote sensing such as that provided by MODIS. Australian researchers have shown how Landsat and MODIS imagery can be blended to produce a product with the spatial resolution of Landsat TM (30 m) and the temporal frequency of MODIS (potentially daily but, realistically, weekly when mosaicked to remove cloud and other forms or aerosol contamination).

     Decay and consumption rates will initially need to be based on remotely-sensed ground cover until suitable methods exist for remotely monitoring pasture biomass. Research by CSIRO scientists in central Australia in the 1990s, among others, have demonstrated the potential to model patterns of defoliation. Their approaches may be worth revisiting, in a similar or modified way. It may be that the types of models developed for arid-zone grazed landscapes can be generalized for known stocking rates on productive land types beyond central Australia. If so, then it may be feasible to include these 'discount' functions in GRASP (or other models) to simulate probable forage remaining at various times since the end of each growing season.

1.8.5 Maximizing value from knowing pasture biomass

Fig. 1-1 illustrated some of the derived benefits for managing livestock and land from knowing how much pasture is available. Also important is knowledge of the error associated with such estimates; whether derived from ground-based assessment, remotely monitored, modelled or a combination of all methods. Pasture biomass translates to forage availability via parameters such as palatability, accessibility (e.g. distance from water) and safe utilisation level. Resultant feed-on-offer directly informs seasonal stocking rate. Making the correct tactical decision here, year in – year out, within the broader context of long-term safe carrying capacity, current land condition and often high inter-annual variability in rainfall determines management effects on land condition, longer-term profitability and, regionally, longer term sustainability of pastoralism as a land use.

Thus, there is a lot riding on getting biomass estimation right – provided the product is suitably delivered to producers and they choose to use it as part of their routine tactical decision making. Accompanying caveats (e.g. estimation error) need to be part of product delivery. The availability of reliable information about pasture biomass at key decision points has the potential to change paddock stocking levels from being either a continuing art or 'business as usual' to a reasonably precise science. This has benefits for optimizing animal performance, maintaining or improving land condition and assuring longer term business profitability.

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