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Site-based and remote sensing methods for monitoring indicators of vegetation condition: An Australian review

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ABSTRACT

Native vegetation around the world is under threat from historical and ongoing clearance, overgrazing, invasive species, increasing soil and water salinity, altered fire regimes, poor land management and other factors, resulting in a degradation of natural ecosystem services. Consequently, maintaining and improving native vegetation condition is a target frequently adopted by natural resource managers and government agencies world-wide. Adequate monitoring of vegetation condition remains a prerequisite for environmental decision-making and for tracking progress towards management goals. Throughout we consider vegetation condition to include the compositional, structural and functional attributes of vegetation relative to undisturbed vegetation of the same type.

Site-based methods have long been used to assess compositional, structural and functional attributes as indicators of vegetation condition, and these methods continue to be used widely today. With developing technologies, remote sensing methods are being employed increasingly for monitoring a range of remotely detectable properties of vegetation, and there is now a growing demand to explicitly integrate the two approaches for mapping and monitoring vegetation condition across a range of scales.

Here we review the attributes of vegetation identified as important for monitoring vegetation condition, those indicators that are best measured using traditional site-based methods and those that are more readily detectable using remote sensing methods, including their application in operational programmes within Australia. Further to this we review recent literature on the integration of the two approaches for monitoring indicators of vegetation condition.

We find that remote sensing methods have the advantage of offering broad scale automated and repeatable methods for monitoring indicators of vegetation condition, but when combined with detailed ecological site-based data, together can improve monitoring for answering ecological questions across a range of scales. Further work, however, is required to effectively integrate the two approaches for mapping and monitoring vegetation condition.

1. Introduction

Native vegetation, comprising extant trees, understorey and ground covers, has long been recognised as an important and valuable resource. It is well known to provide many vital ecosystem services (Costanza et al., 1997) which directly and indirectly benefit humans globally, including production, cultural benefits, and regulation and support services (Yapp et al., 2010). Native vegetation also provides habitat for many threatened and endangered species. Given its recognised importance, many organisations and governments actively seek to understand the spatial and temporal dynamics of native vegetation by undertaking monitoring. Monitoring can help determine the extent and cause of changes to vegetation, such as changes in abundance of species and diversity, incursion of threats, change in vegetation cover, stress or overall changes in condition of vegetation communities. Vegetation condition is considered throughout this paper to be the relative health of vegetation compared to undisturbed vegetation of the same type, including the compositional, structural and functional attributes of the vegetation.

Monitoring native vegetation condition has been undertaken extensively with a diverse range of motivations, including meeting legislative responsibilities, providing accountability for land managers, targeting investment, and meeting international obligations (e.g. United Nations Convention to Combat Desertification

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(UNCCD, 1994); Convention on Biological Diversity (Convention on Biological Diversity, 1992)). In addition, recently emerged environmental markets also require vegetation monitoring to allow informed decision making. These include incentive schemes (Oliver et al., 2005; Parkes et al., 2003), carbon markets (DeFries et al., 2005a), and sustainable farming certification. State of the Environment reporting is also undertaken by a large and growing number of management organisations worldwide, including regional, state, national and international governments and authorities (Lindenmayer and Likens, 2010). Monitoring is also undertaken for forestry plantations around the globe (Coote et al., 2012; Stone and Coops, 2004).

Given the diversity of needs, contexts and purposes, many different programmes have been developed for monitoring vegetation condition. The selection of vegetation indicators for measurement as well as choice of methods are both critical in any monitoring programme. Inappropriate indicator selection is common, and can have significant costs and implications for environmental decision-making (Failing and Gregory, 2003). Importantly, the indicators and assessment methods should explicitly address ecological or management questions, while including considerations such as spatial and temporal scales.

Methods for vegetation monitoring condition traditionally have involved site-based (e.g. typically a quadrat of 1 ha or less, or a 100 m transect) assessments (Gibbons and Freudenberger, 2006; Parkes et al., 2003), however, increasing demand for information at broader scales has seen the application of spatial modelling (Zerger et al., 2006) as well as many remote sensing studies for mapping and monitoring indicators of vegetation condition (Newell et al., 2006; Sheffield, 2006; Wallace et al., 2006). The use of remote sensing for assessing ecological properties of vegetation has been reviewed comprehensively (Asner and Martin, 2009; Gillespie et al., 2008; Kerr and Ostrovsky, 2003; Nagendra, 2001; Schimel et al., 2013; Turner et al., 2003; Ustin and Gamon, 2010). These reviews focus on direct (e.g. species identification and land cover classification) and indirect measures (e.g. modelling patterns of species and diversity) of biodiversity assessment, but they do not consider other structural, compositional and functional indicators relevant for vegetation condition monitoring.

This paper assess the structural (components which make up the three dimensional arrangement of vegetation), functional (ecological processes and vegetation history) and compositional attributes (species richness, diversity, and plant types) which are important for monitoring vegetation condition and how these have been measured using site-based and remote sensing methods, including operational programmes within Australia. We review studies which have integrated the two approaches and highlight how integrated methods are advancing the field of vegetation monitoring and where there is still need for further development.

As climate change and population growth place increasing pressures on our natural resources, improved methods for monitoring vegetation across a range of spatial and temporal scales will be vital for understanding and addressing changes to vegetation. Effective mapping will provide tangible evidence about the condition of native vegetation and will be essential in informing evidence-based decision making, assessing progress towards targets and in environmental reporting.

2. Indicator selection in monitoring

In principle, a comprehensive assessment of vegetation condition should take into account all structural components and ecological processes (above and below ground) and disturbance regimes over all spatial and temporal scales within a system, from individual plants to landscape level (Noss, 1990). However, such a comprehensive census of all vegetation attributes and variables over time throughout the landscape is impossible and impractical, generally constrained by logistics and funding. Some studies, however, have attempted to monitor a long 'laundry list' of vegetation attributes, which has resulted in reduced quality of measurements, increased cost, a reduced number of replicates and a consequent reduction in statistical power to detect trends (Lindenmayer and Likens, 2010). Specialisation is therefore necessary and many approaches have been developed which monitor select subsets of vegetation attributes as indicators of vegetation condition.

The use of indicators to quantify and standardise measurements of vegetation condition has long been suggested by ecologists (Noss, 1990). The choice of indicators to be measured is critical in vegetation monitoring. Mistakes are common in indicator selection, and this can have significant costs and implications for environmental decision-making (Failing and Gregory, 2003). Importantly indicator selection should be guided by the context, specific questions being asked and the spatial and temporal dimensions being addressed. Other considerations include whether the indicators are cost-effective to measure, reliable and repeatable, comparable across vegetation types, can be standardised against benchmarks, are capable of representing the overall condition of a system, are sensitive to disturbance and management, allow continuous assessment over a wide range of stressors, and are ecologically relevant (Noss, 1990).

The considerable diversity of vegetation indicators can broadly be divided into three categories: compositional, structural, and functional indicators (Noss, 1990). Compositional indicators include identity attributes, such as species richness and diversity, vegetation types, presence of threatened species and relative cover of exotic and indigenous species. The link between composition and vegetation condition is well established (McIntyre and Lavorel, 1994). Weed species are known to reduce native species diversity and abundance through competition (Catford et al., 2012; Lake and Leishman, 2004).

Structural indicators are measures of the three dimensional arrangement of the vegetation such as the density of different plant forms, density of tree hollows, canopy cover and ground cover components, patch size and landscape context. Structural components of remnant vegetation are known to be important for influencing microclimates (Chen et al., 1999), providing niches for a wide variety of fauna species, including reptiles and small mammal species (Garden et al., 2007). At a regional scale, landscape context, including the size, shape and configuration of remnants, is widely accepted as important for vegetation condition and ecosystem function (Collinge, 1996). Fragmentation and decreasing connectivity is known to limit dispersal of species (flora and fauna) and therefore genetic diversity (Young et al., 1996). Patch size has long been known to limit the number and diversity of species which can persist in a particular area, as predicted by island biogeography theory (MacArthur and Wilson, 1967). Furthermore, the land use surrounding remnants can impact via edge effects (Ries et al., 2004) either negatively through weed invasion, chemical drift, and damage to roots, or positively through reduced competition for light and nutrients, allowing more vigorous growth of vegetation on edges. Change in landscape structure also affects processes such as fire and spread of disease and weeds. Many landscape metrics exist for characterising the spatial structure of vegetation patches including patch size, contagion, configuration, dispersion, connectivity, and shape complexity.

Functional indicators include ecological processes and vegetation history, such as disturbance history, tree health, and nutrient cycling. Such indicators provide important information on the natural processes occurring within a system. Sites in better condition exhibit evidence of natural processes and are considered more resilient to disturbance.

3. Methods for monitoring indicators of vegetation condition

Two main approaches have been applied to monitoring vegetation condition: site-based assessments and remote sensing methods. The two approaches are distinguished, among other things, by their spatial and temporal scales of application, costs, expertise required, and importantly, the different attributes and indicators that each can measure.

3.1. Spatial and temporal scales of monitoring

Despite site-based monitoring programmes having a long a history of application (e.g. Lawley et al., 2013; Sinclair, 2005), and still being commonly used today, their methods are largely absent from the peer reviewed literature. Site-based monitoring typically involves selecting sites from within homogenous patches of vegetation of the same community type and site history. The majority of site-based assessments are quadrat-based where detailed information is collected about the compositional, structural, and functional attributes of a site (e.g. typically a quadrat of 1 ha or less, or a 100 m transect). In some cases landscape metrics have also been added into overall measures, and benchmarked scores are combined to give an overall condition index for individual patches of sampled vegetation (Department of Environment Climate Change & Water, 2011; Michaels, 2006; Parkes et al., 2003). In Australia, site-based condition assessments are often undertaken in spring when native species are flowering and are more readily identifiable, although may also be undertaken in other seasons. Temporal frequency of site revisits is often limited by government funding cycles. Table 1 contains a non-exhaustive list of site-based operational vegetation monitoring programmes within Australia (since the early 2000s) and the vegetation attributes measured in each. These operational programmes predominantly measure structural and compositional indicators of vegetation condition, with less emphasis on indicators of function.

The scale at which remote sensing studies measure attributes of vegetation condition varies with the sensor used. Sensors vary in their spatial, spectral, radiometric and temporal resolutions of data collection, and therefore their ability to record and monitor attributes of vegetation. Ground resolution varies from 0.5 m to 10 m for high spatial resolution sensors (e.g. IKONOS and WorldView) to 30 m for medium resolution sensors (Landsat) and 250–1000 m or greater for low resolution sensors (MODIS and NOAA AVHRR). The size of the ground resolution cell determines the scale of the individual features that can be detected, and each image pixel may contain a combined reflectance from more than one feature. Cracknell (1998) discussed the issue of these mixed pixels or 'mixels' and the importance of realising the digital number recorded by the sensor is complicated and may not contain a signal for a single feature. Often sensors with the coarsest spatial resolution have a higher temporal resolution, such as AVHRR (1–2 revisits/day) and MODIS (1–2 revisits/day) and sensors with the highest spatial and spectral resolution have limited spatial coverage and temporal archives, so trade-offs need to be made when selecting the imagery most appropriate for monitoring. Wang et al. (2010) provide a recent review of remote sensing technologies, instruments and techniques.

Table 2 lists many of the operational remote sensing programmes used in Australia for monitoring vegetation. These programmes measure vegetation, such as foliage projective cover, proportion of photosynthetic, non-photosynthetic vegetation and soil, or tree density measures, vegetation extent, rangeland vegetation, drought and fires. No programmes have yet been developed which incorporate other measures of condition such as distinguishing between native and non-native vegetation cover.

3.2. Structural, compositional and functional indicators

Historically site-based monitoring of vegetation has been taxon-focussed (Oliver et al., 2002), but also has been applied successfully to measuring other compositional, structural and to a lesser extent, functional indicators of vegetation condition.

3.2.1. Site-based methods

Using expert consultation, Oliver (2002) compiled 62 structural, compositional, and functional indicators which best encapsulate vegetation condition at the scale of the site, for woodland and open forest vegetation communities within New South Wales, Australia. These indicators were later prioritised using multicriteria analysis of 11 of the most important indicators of vegetation condition in these vegetation communities. These indicators were (1) alpha diversity of native trees, (2) cover of native trees, shrubs and perennial grasses, (3) cover of exotic shrubs, perennial grasses, legumes and forbs, (4) cover of organic litter, (5) recruitment of native tree/shrub saplings, (6) native tree health (including dieback and mistletoe presence or absence), and (7) evidence of grazing, 8–11) plus a number of landscape structure attributes (Oliver et al., 2007). These indicators are typical of those used in other studies of vegetation condition both internationally and in Australia (Noss, 1990; Parkes et al., 2003).

Plants used as indicators have included orchid species (Laroche et al., 2012), rangeland species response types (Wesuls et al., 2013), popular edible wild plants (Higa et al., 2013) and plant functional types (Cousins and Lindborg, 2004) among many others. The use of indicator species is based on the assumption that other species will respond to stressors and critical ecosystem processes in a similar way, hence monitoring only need be performed for a single indicator species or taxa. Restricting monitoring to a single species is logistically and economically appealing, provided that the species is not already rare. However, some researchers are sceptical of this method for monitoring condition. Lindenmayer and Likens (2010) point out that not all species are equally sensitive to change and species may behave differently in different landscapes and in response to different stressors. Despite being far more labour intensive and requiring high level expertise during collection, measures of composition are common in vegetation condition monitoring programmes. Shortcomings of site based measures of composition include non-detection errors even for common, persistent vegetation species (Clarke et al., 2012; Elphick, 2008) and inconsistencies between different plot sizes, lack of replication and lack of multiple spatial scales when detecting species richness (Dengler, 2009).

Structural measures are common in site based monitoring programmes and include life form, height, strata and various measures of stem density, canopy and foliage cover. Inclusion of functional indicators has been encouraged for assessing vegetation condition at the scale of the site in order to infer site resilience and future site trajectory (Gibbons and Freudenberger, 2006). Measures of vegetation function are typically limited to observations of tree health and stress including canopy health and presence of plant parasites. Some information can also be inferred about disturbance history, including evidence of grazing, fire, flood, and salinity.

3.2.2. Remote sensing methods

The ability of remotely sensed tools to measure attributes of vegetation varies with the sensor, the background characteristics, and which vegetation indicators are to be detected.

The spatial resolution (ground resolution and image extent), spectral properties (number of bands, their width and location within the spectrum), temporal resolution (frequency of

Table 1
Examples of site-based vegetation condition monitoring methods/programmes in Australia.

Method	Indicators measured	Year commenced	Reference	Comments
Rapid Appraisal of Riparian Condition (RARC)	Site: Cover, canopy, logs, leaf litter cover, regeneration, grazing pressure, strata.	2003	Jansen et al. (2003)	Developed as a tool to determine the impacts of grazing management practices on riparian condition.
Habitat Hectares	Site: Large trees, canopy cover, understorey, weeds, recruitment, organic litter, logs. Landscape context: Patch size, neighbourhood, distance to core area.	2003	Parkes et al. (2003)	Developed to quantify site-based vegetation condition for use in a market-based mechanism ('Bush Tender') for purchasing land management services in Victoria.
Bushland Condition Monitoring (BCM)	Site (30 m × 30 m quadrats): Diversity of flora, weeds, structural diversity, regeneration, tree health, tree habitat features, feral animals, grazing pressure, fauna species diversity.	2005	Croft et al. (2005)	Used within South Australia.
BioCondition	Site (transect of 100 m × 50 m): Large trees, canopy cover, richness, coarse woody debris, understorey, organic litter cover.	2006	Eyre et al. (2006)	Used within Queensland as a vegetation condition assessment tool. Based on Habitat Hectares.
TasCondition	Site: Large trees, canopy cover, understorey, weeds, recruitment, persistence potential, organic litter, logs. Landscape context: Patch size, neighbourhood, distance to core area.	2006	Michaels (2006)	Based on Habitat Hectares.
Vegetation Assets States and Transitions (VAST) model and VAST-2	Site: Regenerative capacity, structure and composition. Condition states include residual, modified, transformed, replaced/adventive, removed/replaced/managed.	2006	Thackway and Lesslie (2006)	Designed as a management tool for measuring and reporting vegetation condition. Uses site-based assessments, remote sensing and modelled data sets and can be used Australia-wide.
AusPlots (Terrestrial Ecosystem Research Network)	Site: Perennial and annual species richness, genetic profile (DNA and isotope), basal area, cover of upper, middle and lower strata, LAI, soils.	2012	White et al. (2012)	Used for informing research, management and conservation strategies in Australia's rangelands. Estimated sampling time 8–17 h for an average plot.
Biodiversity Fund Ecological Monitoring Guide	Site: Native and exotic ground cover, exotic fauna, canopy cover native and exotic, crown type, species diversity	2013	Department of Sustainability Environment Water Population and Communities (2013)	Based on commonly used vegetation monitoring methods around Australia. Specifically designed for reporting under the Biodiversity Fund, Clean Energy Future Plan, Caring for our Country programme.

acquisitions) of the sensor, as well as the time of year also influence the vegetation features that can be detected. Additionally, vegetation attributes of individual species such as size, shape, aggregation, extent of distribution and phenology can determine whether the species is detectable with remote sensing. The physical structure of vegetation is also important as, for example, canopy cover influences the level of signal measured from the understorey and substrate. If the features to be detected are spectrally distinct from their surrounds they have a greater chance of being successfully discriminated through image analysis. Knowledge of the characteristics of the attribute to be measured must be used to inform the selection of appropriate imagery for detection and analysis.

3.2.3. Composition

Remote sensing studies have aimed to map vegetation composition ranging from vegetation functional types and communities to individual species, including native and exotic species. Vegetation composition has been mapped with multi-spectral satellite imagery (Lewis, 1994, 1998; Sivanpillai and Ewers, 2013), hyperspectral imagery (Lewis et al., 2001; White et al., 2013), high spatial resolution multi-spectral imagery such as IKONOS (Dillabaugh and King, 2008; Johansen and Phinn, 2006) and high spatial and spectral resolution imagery such as CASI (Bunting and Lucas, 2006; Lewis, 2000; Lewis et al., 2001). Lidar has also been recognised for its potential in mapping forest diversity when used in conjunction with measures of leaf chemistry and spectral signatures (Asner and Martin, 2009). Historically composition has been harder to derive from remotely sensed imagery than vegetation structure, although there has been some progress in this area. For example, species richness and diversity have been found to be related to remotely sensed spectral (Redowan, 2013) and textural measures (Rocchini, 2007; Rocchini et al., 2010).

Vegetation type has been derived from remotely sensed imagery using a number of different feature extraction techniques, including vegetation indices and spectral classification. Broad vegetation cover classes and land use types have been generated with the use of NDVI (Hill et al., 1999), although this does not discriminate well between vegetation communities. Phenology has been used to distinguish different vegetation types using hypertemporal coarse resolution data e.g. AVHRR and MODIS (Jeganathan et al., 2010; Lawley et al., 2011; Petus et al., 2013). Supervised classification, using pre-selected reference areas as spectral training sites, has long been used in studies seeking to discriminate vegetation types (Lewis, 1998; Nagendra and Gadgil, 1999; Sesnie et al., 2010).

Table 2
Operational programmes in Australia for mapping and monitoring terrestrial vegetation using remote sensing, adapted from Turner et al. (2013), ACILTasman (2010) and GeoscienceAustralia (2011).

Programme	Organisations	Product/indicators measured	Coverage	Satellite/sensor
National Carbon Accounting System-Land Cover Change Project (NCAS-LCCP)	Department of Climate Change, CSIRO, Australian National University	Land cover change including, forest cover, non-forest cover, sparse perennial vegetation cover, regrowth, clearance, constant forest, constant non-forest, sparse vegetation, hardwood and softwood plantations, environmental planting, new forests and plantations, vegetation density index. Some products as early as 1972 and updated annually.	Australia	Landsat, QuickBird, IKONOS
Native Vegetation Information System (NVIS)	Department of Environment, Water, Heritage & the Arts; Department of Agriculture, Fisheries & Forestry	Extent and distribution of vegetation types in Australia.	Australia	Landsat, SPOT, MODIS
Parks Australia	Department of Environment, Water, Heritage & the Arts	Whole of park imagery used for park management, and obtained twice or three times per year.	Australia	Landsat, SPOT, Geoeye, Worldview, Aerial Imagery
Environmental Resources Information Network (ERIN)	Department of Environment, Water, Heritage & the Arts	ERIN develops and manages an information base for environmental decisions for a range of environmental themes.	Australia	Landsat, SPOT, Geoeye, Worldview, MODIS, AVHRR
National Land Cover Mapping	Geoscience Australia; Bureau of Rural Sciences and Australian Bureau of Agricultural and Resource Economics and Sciences within the Department of Agriculture, Fisheries & Forestry	Dynamic land-cover mapping, including current and historical, change detection and environmental reporting at a national, regional and local scale.	Australia	Landsat, MODIS
National Forest Inventory	Department of Agriculture, Fisheries & Forestry	Forestry data for monitoring and reporting. The inventory aims to provide a single authoritative source of forestry data at the national level.	Australia	Landsat
National Land and Water Resources Audit	Department of Agricultural, Fisheries & Forestry	Changes in natural resources over time. Ended in 2008.	Australia	Landsat, Aerial Imagery
AusCover – Terrestrial Ecosystem Research Network (TERN)	Coordinated by CSIRO's Marine and Atmospheric Research Division	A network for terrestrial ecosystem research. Wide range of remote sensing products including fractional ground cover, persistent green vegetation, land cover (34 classes) dynamic land cover, trends in EVI (Enhanced Vegetation Index), photosynthetic, non-photosynthetic vegetation and soil. A national biomass map is about to be released.	Australia	Landsat, MODIS, ALOS, Aerial Imagery
Bushfire Cooperative Research Centre	Fire and land management agencies in Australia and New Zealand, including CSIRO, the Bureau of Meteorology, the Attorney General's Department and several other fire related organisations	Grasslands curing assessment. NDVI used to quantify vegetation condition/phenological stage. No longer funded.	NSW/VIC	MODIS and Meteorological satellite data
WA Land Monitor Project (Based on NCAS-LCCP)	CSIRO, Landgate, Department of Parks & Wildlife, Department of Agriculture & Food Western Australia, Department of Water, Water Corporation, and the Department of Planning & Infrastructure	Perennial vegetation cover, vegetation density index, and changes in vegetation cover and trends. Monitoring 1988–present.	Southwest WA	Landsat, MODIS, SPOT, ASTER, NOAA (AVHRR), QuickBird
Hi-Res Landmonitor Southwest WA	CSIRO	Extent of woodlands, including reserves, creekline and wetland fringing vegetation, as well as environmental plantings for the Landmonitor region.	Southwest WA	MODIS, SPOT, ASTER, NOAA (AVHRR), QuickBird
CarbonWatch	Landgate	Online carbon accounting tools to plan, monitor, quantify and report on carbon sequestration projects.	WA	Landsat, Aerial Imagery
VegetationWatch	Landgate	Greenness image maps over Australia with near real time image updates.	WA	Landsat, MODIS
Vegetation Monitoring	Department of Parks & Wildlife	Pastoral Lease vegetation condition monitoring across WA's rangelands.	WA	Landsat, ALOS, Quickbird
Forest Management Plan 2014–2023	Department of Parks & Wildlife	Forest health, mapping the extent of episodic drought, frost and insect pest impacts on the condition of the forest canopy.	WA	Landsat
Rangeland Monitoring	Department of Parks & Wildlife	Rangeland Monitoring, particularly of ex-pastoral estate turned conservation state.	WA	Landsat

Table 2 (*Continued*)

Programme	Organisations	Product/indicators measured	Coverage	Satellite/sensor
ZY-3 application development	Department of Parks & Wildlife, CSIRO, National Administration of Surveying Mapping & Geoinformation of China	Development of applications using the ZY-3 sensor to map and monitor natural resources in Western Australia. Examples include high resolution woody vegetation mapping and monitoring salinity affected catchments.	WA	ZY-3
Biomass monitoring, ground cover monitoring and regional ecosystem mapping	Department of Natural Resources & Mines	Above ground woody vegetation, groundcover ecosystem mapping, extent and conservation status of remnant vegetation. Used for vegetation clearance applications and property management plans	QLD	Landsat, ALOS Palsar, IceSat, RADAR. SPOT
Queensland land-use monitoring programme (QLUMP)	Department of Natural Resources & Mines	Landuse mapping is performed according to the Australian Land Use and Management Classification (ALUM).	QLD	SPOT, Landsat
Statewide Landcover and Tree Study (SLATS)	Department of Natural Resources & Mines	Overall cover of woody vegetation. Land clearing. Developing methods for mapping and monitoring woodland thickening (increase in density of woody plants, trees and shrubs, in savanna woodlands in QLD).	QLD	Landsat
NSW Woody Vegetation Monitoring Programme (based on Qld. SLATS)	Office of Environment & Heritage	Woody extent and overstorey foliage projective cover. Annual changes in woody vegetation cover (clearance only). Statewide vegetation mapping.	NSW	Landsat, SPOT (10 m and 2.5 m)
Rural Floodplain Management	Office of Environment & Heritage	Mapping of vegetation communities in floodplains.	NSW	Aerial photography, Spot 5
Elevation and vegetation structural mapping	Office of Environment & Heritage	Vegetation structure	NSW	Lidar
Monitoring State of the Catchments	NSW Office of Water	Catchment and riverine vegetation monitoring	NSW	Landsat
Plant community type mapping	Office of Environment & Heritage	Plant communities mapped on a state wide catchment scale	NSW	SPOT & ADS40/80
Vicmap Vegetation	Department of Environment and Primary Industries	Tree density (dense, medium, scattered). Based on imagery 1993 – 2001	VIC	SPOT Pan (2 m)
Native vegetation extent and condition	Department of Environment and Primary Industries	Native vegetation type, extent, and condition	VIC	Landsat, SPOT, MODIS, ALOS, SRTM
Change detection programme	Department of Environment & Natural Resources	Illegal vegetation clearance	SA	Landsat, Aerial Imagery
Land Cover Programme – Tasmania	Department of Primary Industries, Parks, Water & Environment	Currently being set up with assistance from QLD SLATS programme. Total forest cover, facilitating the update of vegetation mapping, the establishment of landscape burn histories, monitoring long term trends and short term impact events on Tasmania's woody vegetation.	TAS	Landsat
TasVeg: Tasmanian Vegetation Mapping and Monitoring Programme	Department of Primary Industries, Parks, Water & Environment	Mapping vegetation	TAS	Spot, Aerial Imagery
Land Planning and Land Authority	Environment & Planning Directorate	Land use monitoring, mapping, catchment management, bushfire detection and management.	ACT	SPOT, MODIS, meteorological imagery, Aerial Imagery
Northern Territory Land Information Systems	Department of Lands, Planning & the Environment	Rangeland monitoring	NT	Landsat

These image analyses lend themselves well to homogenous vegetation stands, although they perform less well in classifying mixed vegetation stands (Teillet et al., 1997).

Identifying species and communities has become increasingly possible with hyperspatial and hyperspectral imagery (Schimel et al., 2013; Turner et al., 2003), due to the greater separability of spectral signatures and vegetation spatial structure. Much research has focussed on detecting weed species (Cuneo et al., 2009; He et al., 2011; Mirik et al., 2013a,b; Somers and Asner, 2013; Ustin et al., 2002), the cover of which is known to be a key indicator of vegetation condition (Oliver et al., 2007). Phenology of species has also been helpful in identifying vegetation species in remotely sensed imagery (Hill et al., 2010; Somers and Asner, 2013), even with relatively spatially coarse MODIS data (Zhou et al., 2013). The variation in spectral reflectance over different seasons highlights the importance of selecting comparable imagery for time-series analysis.

3.2.4. *Structure*

Of the compositional, structural and functional attributes typically used to monitor vegetation condition, remote sensing has been most successful at measuring structure, particularly vegetation cover, height, and stem density. There has been little success in remotely sensed measures of tree hollows (Catena et al., 1990) or in detecting fallen logs and woody debris (Huang et al., 2009).

Vegetation cover and density are the attributes most commonly derived in remote sensing studies of vegetation, and have been measured at scales ranging from global (Defries and Townshend, 1994; Hansen et al., 2000) through regional studies (Nagler et al., 2001) down to individual trees (Leckie et al., 2003). Measures of remotely sensed vegetation cover and density include foliage projective cover (Armston et al., 2009), woody and non-woody cover (Furby et al., 2009; Radford, 2005), and biophysical (functional) properties such as leaf area index and absorbed photosynthetically active radiation (Myneni et al., 1997).

Many researchers have focussed on land cover classification (Friedl et al., 2002; Hansen et al., 2000; Loveland et al., 2000; Tucker et al., 1985) and monitoring change in vegetation cover, including vegetation clearance (Asner et al., 2005; Hansen et al., 2010) and the dynamics of vegetation over time (Lawley et al., 2011). Patterns of vegetation cover have often been quantified using landscape metrics such as isolation (DeFries et al., 2005b) and fragmentation (Nagendra et al., 2004), which are well known to have significant impacts on vegetation condition (Saunders et al., 1991).

Vegetation indices are commonly used to quantify vegetation cover, vigour and density in remote sensing. The Normalised Difference Vegetation Index (NDVI), which distinguishes actively growing vegetation from background features, is the most widely used vegetation index in remote sensing studies (Hansen et al., 2000; Loveland et al., 2000; Southworth et al., 2004). Other indices for measuring cover commonly used include the Soil Adjusted Vegetation Index (SAVI), Enhanced Vegetation Index (EVI) (Karnieli et al., 2013), Modified Soil Adjusted Vegetation Index (MSAVI) and the Transformed Soil Adjusted Vegetation Index (TSAVI) (Qi et al., 1994). As each of these vegetation indices perform differently in different environments (Jafari et al., 2007; Purevdorj et al., 1998), research is often needed to identify which is most appropriate for a particular application.

Measures of vegetation height can be derived using LIDAR and RADAR (Dubayah and Drake, 2000; Hyyppa et al., 2001; Lefsky et al., 2002b). LIDAR has also been used for measuring forest leaf area index (LAI) (Luo et al., 2015), canopy structure and biomass (Lefsky et al., 2002a). Whilst LIDAR and RADAR are used for forestry applications they are uncommon in monitoring native vegetation of conservation interest, likely due to the high costs associated with imagery from these sensors and the specialist processing required.

Other structural features such as fallen logs and trees, and tree hollows are often measured in site-based condition assessments, although limited work has been done on detecting these with remote sensing, because of the difficulty of detecting them. However, because of the known relationship between presence of hollows and tree size for certain species (Lindenmayer et al., 2000; Wormington and Lamb, 1999), it may be possible to derive this condition measure indirectly using remote sensing.

Canopy health and insect damage have been successfully derived from remotely sensed data, largely using hyperspectral imagery, in Eucalypt species (Coops et al., 2001; Evans et al., 2012; Haywood and Stone, 2011; Pietrzykowski et al., 2007; Stone and Coops, 2004; Stone and Haywood, 2006) and aspen and pine species (Coops and Stone, 2005; Hall et al., 2003; Ismail et al., 2007; Poona and Ismail, 2013; Sims et al., 2007; Stone et al., 2003, 2013). Such measures can be linked with vegetation condition and may provide improved quantitative measures compared to site-based assessments of tree health.

Plant regeneration is an important vegetation attribute and can be detected to some extent using multi-spectral imagery, texture measures or inferred through remotely sensed height measures (Holmgren and Persson, 2004; Leckie et al., 2003). However, the ability to detect very young stands of regenerating trees is limited (Korpela et al., 2008). Measures of plant regeneration can be informed by changes in land cover through change detection analysis including increases in cover (Lunetta et al., 2004) and changes in canopy roughness as vegetation ages (Foody and Curran, 1994; Kuplich et al., 2005); however methods are not well developed.

3.2.5. Function

Remote sensing has been very useful for measuring vegetation functional attributes, largely relating to primary production, plant health and phenology, disturbance including grazing, fire and floods. Much research has focused on studying vegetation health through measures of vegetation moisture (Gao, 1996; Penuelas et al., 1993), biochemical properties of plants including chlorophyll content (Coops et al., 2003; Houborg et al., 2011), and other leaf pigments (Sims et al., 2007). Lignin and nitrogen content have also been measured using remote sensing to infer ecosystem functioning (Martin and Aber, 1997). Primary productivity, arguably the most important functional attribute of plants, has also been widely estimated using remote sensing (Mirik et al., 2013a; Running et al., 2004; Song et al., 2013). Such measures have rarely been measured in traditional site-based assessments and therefore offer a new perspective on monitoring vegetation condition.

Zarco-Tejada et al. (2009) used chlorophyll fluorescence imaging to detect stress in vegetation, which is a pre-visual indicator of stress. Physiological and structural indicators of water stress in vegetation have also been measured, including wilting and loss of leaf area (He et al., 2011). Several studies also have successfully used canopy temperature as an indicator of vegetation stress (Bellvert et al., 2014; Rud et al., 2014).

Many causes and indicators of vegetation disturbance have been derived successfully from remotely sensed data, including weather (Kogan, 1990), fire (Justice et al., 2002; Turner et al., 2008), soil salinity (Dutkiewicz et al., 2009a,b; Metternicht and Zinck, 2003), and grazing (Bastin et al., 2012; Pickup et al., 1994). Tree mortality due to drought, wildfire and changes in management activity have also been detected using remote sensing methods (Garrity et al., 2013).

4. Integration of site-based and remote sensing for monitoring vegetation condition

In Australia information about vegetation condition is sought across a range of scales from paddocks and sites to regions and the continent. By linking remotely sensed data with site-based data, ecological questions can be addressed across a range of spatial scales. Two broad forms have been used to integrate site-based data and remote sensing data together.

The most common approach involves the use of site-based data to characterise training sites and/or assess the accuracy of classifications from remote sensing analysis. Sometimes the relationship between site-based data and remote sensing data is statistical and explicit (Lewis, 1998); but more frequently is in the form of accuracy assessments. The second approach uses site-based data to calibrate and validate remote sensing indices and measures, where the remote sensing variable is used to predict the same biophysical variable on the ground (e.g. percent cover and LAI). Some studies also test the predictive relationships with independent validation sites e.g. SLATS (Table 2) and Cunningham et al. (2009). Typically, when the imagery has a higher resolution than the objects of interest the first approach is used e.g. for classification of vegetation types using Landsat data; but when the imagery has a lower resolution than the objects of interest e.g. fractional cover derived from the unmixing or vegetation indices, the percentage cover is smaller than a pixel and hence image variables are related to site-based variables via statistical relationships such as correlations and regression analysis, as in the second approach (Strahler et al., 1986).

Site-based vegetation condition data has been integrated with remotely sensed imagery with varying degrees of success. Coops et al. (1997) assessed the linear relationships between LAI site-based data with NDVI and the SR (simple ratio) derived using Landsat MSS data, yielding R^2 values on 0.71 and 0.53 respectively.

Cunningham et al. (2009) tested four different modelling methods for mapping site-based health of *Eucalyptus camaldulensis* across a 1600 km length of river floodplain, yielding R^2 values between 0.77 and 0.85; however subsequent ground validation showed lower predictive power of the models in some cases. Sheffield (2009) compared data from the site-based BioMetric method (Department of Environment Climate Change & Water, 2011) with multi-spectral remotely sensed data using linear regression and found that some vegetation cover measures and stem density measures showed reasonable correlation with the imagery (R^2 values 0.58 and 0.76 respectively). However not surprisingly, most other site based variables were very poorly correlated, including understorey cover, litter, rocks, and hollow-bearing trees. Overall site condition scores showed moderate correlation with the imagery, yielding an R^2 value of 0.55. A number of state and national programmes within Australia also explicitly link site based structural measurements with remotely sensed data, including the foliage projective cover in NSW and AusCover etc. (Table 2). Landsat data and Spot 5 imagery has also been linked with windscreen assessment data using a ground cover index (GCI) to map attributes of very poor rangeland condition including density of grasses, soil condition, presence of weed species and woody vegetation density (Karfs et al., 2009). Whilst very poor condition classes were identifiable, other land condition classes (from good to poor) were less identifiable in the imagery (Karfs et al., 2009).

In order to explicitly link site-based and remotely sensed measurements a number of considerations must be taken into account. Often the design of traditional site-based monitoring programmes does not enable easy integration with remotely sensed data, creating difficulties with data integration, including data quality standards and the spatial and temporal mismatch between data collections (Reinke and Jones, 2006). Reinke and Jones (2006) highlight the importance of plot location within homogenous patches to avoid the effect of mixed pixels, the need for reference points for data alignment, the need for correspondence between the size of site-based plots and image samples, an adequate number of plots which represent the variation in the vegetation, and the importance of matching dates of data acquisition. Zerger et al. (2009) also highlighted the importance of stratified site-based sampling which captures disturbance gradients in order to improve broader scale mapping of vegetation condition.

Continual work in this field will be vital for producing a consistent set of guidelines for integrating site and remotely sensed data, in order to effectively map and monitoring vegetation across a range of scales. The ecological field data must be collected in a systematic way and could be designed to measure those attributes which can more readily detectable in remotely sensed imagery. Notably the synoptic coverage and temporal frequency of remote sensing is very good at capturing environmental variability and may be used to improve design of site-based sampling (Ostendorf, 2011).

5. Synthesis

Given the state of decline of vegetation condition in Australia, improved monitoring over a range of spatial and temporal scales is urgently required. The limited budget and capacity for assessment of vegetation condition necessitates cost effective indicators and methods that can be explicitly linked to condition. Site-based and remote sensing methods have proven very valuable in advancing the field of vegetation monitoring at their relative scales of application. However, effective integration of the two approaches will be key to accurately mapping and monitoring indicators of vegetation condition across a range of spatial scales and in answering pressing ecological questions.

This review has assessed attributes and methods for monitoring vegetation condition, including their spatial and temporal scales of application. Remote sensing offers broad scale, readily repeated measures of vegetation attributes and the possibility of 'lead' non-visible indicators such as monitoring water stress in vegetation. Remote sensing is also particularly suited to change detection, whilst site-based studies offer important measures of biophysical attributes. Studies which integrate the two approaches offer the benefit of assessing vegetation condition across a range of spatial and temporal scales, however, are still in their infancy and several challenges need to be overcome. Despite challenges to integration of data types, much more can be achieved in this field. For example, site-based monitoring could be extended to also measure indicators of condition which are more readily estimated with the imagery e.g. measures of canopy health.

In the future technological advancements such as imaging spectroscopy and LIDAR, the increasing free availability of satellite image time series, and online sharing of ecological data through crowd sourcing and open access datasets, will enable further development in this field of mapping and monitoring vegetation across a range of scales. Conservation drones or unmanned aerial vehicles (Oliver et al., 2014) could also be useful in vegetation condition monitoring as they can coincide with the timing of site-based assessments; although they are also limited in coverage due to restricted flight time. Such developments may provide improved understanding of the complex spatial patterns and processes of vegetation, which is crucial for evidence-based natural resource management (Ostendorf, 2011) and quantifying vegetation condition across a range of scales.

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