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Key attributes for monitoring and assessment of Australian forests: a land management perspective

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Abstract
The rapid technological development of active and passive remote sensing has proved of great value for forest monitoring and assessment worldwide. To make full use of this development, Australian land managers need efficient routines and tools tailored for operations in Australian landscapes. The development of these tools should focus on the most important forest attributes from a land management perspective. This paper presents the results of a web-based survey sent to people directly or indirectly involved in land management. The survey results indicate their current needs in terms of key forest attributes necessary for efficient management, decision making, and for fulfilling reporting obligations. Tree height, canopy health and condition, crown density, floristic composition, aboveground biomass, stem density, forest extent, and fire frequency/severity were among the most important attributes identified by the survey respondents. Moreover, many respondents highlighted the importance of continuous monitoring over time in order to detect changes. A literature review was conducted to examine how primary attributes can be combined to form composite attributes for a variety of purposes. A composite attributes, such as canopy health or aboveground biomass, can be estimated based on a combination of primary attributes. A primary attribute can be equally important as a composite product, if it is necessary for its accurate estimation.

Key words: forest attributes, forest monitoring, forest assessment, forest inventory

Author biography: Christoffer Axelsson has a M.Sc. in Surveying from Lund University. He then worked with GIS and spatial databases in Sweden, in both local government and the private sector, before returning to academia to nurture an interest in remote sensing, and environmental monitoring and modelling. In 2011 he graduated from University of Twente with a M.Sc. in Geo-Information Science and Earth Observation for Environmental Modelling and Management. Currently, he is doing a PhD at RMIT University. Christoffer's main interests are in environmental analysis and modelling using remote sensing technologies.

Introduction
Australia is the world's sixth largest country with an area of 769 million ha, and has a total forested area of 149 million ha (Commonwealth of Australia 2012). These forests constitute an important natural resource by providing timber, supplying fresh water, sequestering carbon, and playing host to a large variety of life forms, many of which are endemic to the continent (Brack 2007). As a participant in the Montréal Process, Australia has agreed to report on the state of its forests using a set of criteria and indicators for biodiversity conservation and sustainable management (Montreal Process Implementation Group for Australia 2008). For monitoring and assessment, Australian land managers are in need of operational and cost-efficient remote sensing tools. Currently, many forest managers rely on field plots, aerial photography surveys, and vegetation indices based on space borne sensors. There is a growing interest in the development of light detection and ranging (LiDAR) technology, data fusion, and efficient up-scaling methods. Airborne LiDAR is of particular importance in forest inventories because it detects the three-dimensional vegetation structure, and enables estimation of structural attributes, such as canopy height, stand basal area, and stem density, with higher accuracy than earlier technologies. The field of remote sensing is constantly evolving and the trend goes towards better sensors, higher spatial and spectral resolution, more data sources and more possibilities to combine different datasets. The technological development of active and passive remote sensing has proved of great value for forest monitoring and assessment worldwide. These technologies are increasingly ready for operational applications at reasonable cost. However, many forest managers still lack the necessary routines to make remote sensing tools an integral and cost-efficient part of their operations. In order to target the development of routines and operational procedures to their specific needs, we need to investigate which forest attributes are the most important from a land management perspective.

This paper presents the results of a web-based survey sent to professionals involved with forest management predominately in Australia and a few in New Zealand. The aim of the survey is to identify core attributes for forest characterisation of importance for both commercial and ecological interests. The survey results provide us with a direct comparison of attribute importance,

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which we were not able to find in the existing literature. The literature is predominately influenced by experiences from Europe and North America. Our results should reflect needs related to the characteristics of Australian forests, and Australian regulations and reporting policies.

Forest attributes

Forest inventories are often based on field plots where a variety of structural and floristic attributes are measured. Using remote sensing data, it is possible to model relationships with the plot data and create forest attribute maps over larger areas (McRoberts *et al.* 2010). Table 1 contains a list of forest attributes, compiled from the literature (e.g. McElhinny *et al.* 2005) and our own experience. The list is not exhaustive but aims to capture some of the most useful attributes at characterising forests for both ecological and silvicultural purposes.

Table 1 Attributes for forest characterisation, grouped under the stand element they describe.

Forest stand element	Attribute
Foliage	Foliage projective cover (FPC) Leaf area
Vertical structure	Canopy height Canopy height profiles (CHP)
Horizontal structure	Canopy/crown cover Stand basal area Stand volume Standard deviation of Diameter at Breast Height (DBH) Stem density Stem clustering, e.g. Clark-Evans Index (Clark and Evans 1954)
Deadwood	Coarse woody debris (number, volume, or basal area of stags) Litter (biomass or cover)
Floristics/type	Dominant type/species Species diversity/richness
Foliar biochemistry	Leaf chlorophyll content Leaf water content

Most of the attributes in Table 1 are commonly estimated from remote sensing data, but some (course woody debris and litter) are extremely difficult. Our aim is not to examine how the attributes are estimated, but to evaluate their importance and show how they potentially can be combined into composite attributes. While many of them carry important information by themselves, an even greater source of information comes from combining them in different ways. The literature indicates that this small set of attributes is informative for a wide range of applications. These applications can be called *composite attributes* since they are estimated from a combination of *primary attributes*. Table 2 gives examples of relationships between primary and composite attributes.

Table 2 Composite attributes and the primary attributes informative for predicting them.

Composite attribute	Primary attribute	Reference
Aboveground biomass and carbon	Canopy height	(Lefsky *et al.* 2002; Koch 2010)
	Stand basal area	(Jonson and Freudenberger 2011; Asner *et al.* 2012)
	Canopy/crown cover	(Lefsky *et al.* 2002; Lucas *et al.* 2008)
	Course woody debris	(Stokland 2001; Keith *et al.* 2009)
	Dominant type/species	(Anderson *et al.* 2008; Koch 2010)
Biodiversity	Standard deviation of DBH	(Van Den Meersschaut and Vandekerkhove 2000; Neumann and Starlinger 2001)
	Coarse woody debris	(Stokland 2001; Grove and Meggs 2003)
	Species diversity/richness	(Lindenmayer *et al.* 2000; Van Den Meersschaut and Vandekerkhove 2000; Clark *et al.* 2005)
Canopy health	Leaf area	(Solberg *et al.* 2006; Stone and Haywood 2006)
	Leaf chlorophyll content	(Coops *et al.* 2003; Rossini *et al.* 2006)
	Leaf water content	(Pontius *et al.* 2005; Chávez *et al.* 2013)
Fire hazard and risk	Canopy height profiles	(Tanskanen *et al.* 2005; Jain and Graham 2007)
	Stem density and clustering	(Graham *et al.* 1999; Richardson and Moskal 2011)
	Litter	(Link *et al.* 2006; Gould *et al.* 2011)
	Dominant type/species	(Graham *et al.* 1999; Gonzalez *et al.* 2006)

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	Leaf water content	(Ustin *et al.* 1998; Ceccato *et al.* 2001)
Forest age and successional stages (including identification of old-growth forest)	Stand basal area	(Ziegler 2000; Kanowski *et al.* 2003)
	Standard deviation of DBH	(Spies and Franklin 1991; Wimberly and Spies 2001)
	Stem density	(Spies and Franklin 1991; Woinarski *et al.* 2004)
	Coarse woody debris	(Spies and Franklin 1991; Kanowski *et al.* 2003)
	Dominant type/species	(Franklin and Spies 1991; Woinarski *et al.* 2004)
Forest extent and categorisation (Australia)	Canopy height	(Montreal Process Implementation Group for Australia 2008)
	Crown cover	(Montreal Process Implementation Group for Australia 2008)
	Dominant type/species	(Montreal Process Implementation Group for Australia 2008)
Timber volumes	Canopy height	(Næsset 1997)
	Stand basal area	(Means *et al.* 2000; Burkhart and Tomé 2012)
	Stand volume	(Maltamo *et al.* 2004; Tonolli *et al.* 2011)
	Dominant type/species	(Tonolli *et al.* 2011)

These relationships between primary and composite attributes are not necessarily generic. All ecosystems are different and the list of significant attributes and their level of influence varies. Which attributes that are used in a specific case will also depend on data availability and quality, collinearity between datasets, as well as methodology. Some attributes are mutually exclusive. For example, LiDAR-based estimates of aboveground biomass and carbon generally use either a combination of canopy cover and height (Koch 2010), or a combination of basal area and height (Asner *et al.* 2012). In both cases, stratification based on species composition is important for obtaining reliable estimates.

There are numerous methodologies for combining attributes. For example, Gonzalez et al. (2006) developed a model for forest fire probability in Catalonia, Spain, using different structural attributes, species composition, and altitude. They found that dense stands, high variety in DBH, dominance by coniferous species, and low altitude were significant in modelling fire occurrence. Canopy health and biodiversity are two fairly subjective composite attributes. In field based studies, there are methodologies for combining attributes using indices, where estimates of different attributes are added together to yield a final score. The Crown Damage Index (CDI), developed for estimating canopy health in eucalypt plantations, is one example. Estimates of crown defoliation, dead leaf tissue, and discoloration each contribute equally to the final CDI score (Stone *et al.* 2003). Van Den Meersschaut and Vandekerkhove (2000) constructed a similar index for assessing biodiversity in forest stands. A whole range of structural and floristic attributes contribute to the final score. All the attributes in these two indices might not be detectable using remote sensing, but a similar approach could be taken to create canopy health and biodiversity indices from attributes that are predictable from air or space.

Forest attribute survey

We constructed a web-based survey with the objective to learn about land managers' needs for forest attributes. The SurveyMonkey web survey application (SurveyMonkey, Palo Alto, CA) was used for constructing the survey form and compiling the results. It was sent on May 4th, 2012, with the deadline set to May 31st. The survey was sent to 81 people of whom 32 responded. The respondents were directly or indirectly engaged with forest management, at a variety of agencies; state and federal government, private companies, and universities. Most were active in Australia and a few in New Zealand.

Table 3 Questions asked in the survey form.

#	Question	Type	Rationale
1	What type of agency do you work for?	Multiple choices. One answer allowed.	Learn about the perspective of the respondents.
2	What is your primary land management responsibility?	Multiple choices. One answer allowed.	Learn about the perspective of the respondents.
3	What data do you currently utilise for forest assessment and reporting?	Multiple choices. One answer per category.	Learn about current inventory methods.
4	What are the five most important forest metrics to capture using remote sensing from a forest management perspective?	Open-ended question.	Let the respondents brainstorm their own list of metrics.

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5	Rank the importance of forest metrics from a forest management perspective.	Multiple choices. One answer per metric.	Let respondents rank our list of metrics.

The survey contained five questions (Table 3) about both forest attributes and the professional background of the respondents. The respondents were not forced to fill in answers to all parts of the survey form. In questions 3 and 5, respondents could tick some of the choices and leave others blank. Results for those questions are therefore presented in % of received answers. Question 4 is open-ended and generated a variety of answers. These were then grouped together with answers of similar meaning. The term *forest metric*, in questions 4 and 5, is used interchangeably with forest attribute. For question 5, we compiled a list of important forest attributes based on the literature and our own knowledge. Question 4 was intentionally placed on a page before question 5 so that the respondents did not see our list of forest metrics before compiling their own.

Results

Of the 32 survey respondents, about half were employed by state agencies and most of these were engaged with either timber production or biodiversity/conservation (Table 4). The second largest employment type was research institute.

Table 4 Employment type and primary responsibility of respondents.

Primary responsibility \ Employment type	Federal agency	State agency	Research institute	Private sector	Total
Timber production	1	5	1	1	8
Biodiversity/ Conservation	1	7		1	9
Water	1				1
Fire management		2			2
Research	2	3	6	1	12
Total	5	17	7	3	32

Figure 1 shows which data is currently used in forest inventories. Respondents with "research" as primary responsibility are displayed as a separate group in order to highlight differences between current operational and research methodologies. All of the listed methodologies are widely used, either routinely or occasionally. The more routinely used methodologies are field monitoring plots (72% of respondents), followed by spaceborne multi- or hyperspectral imagery (65%), and aerial photography (62%).

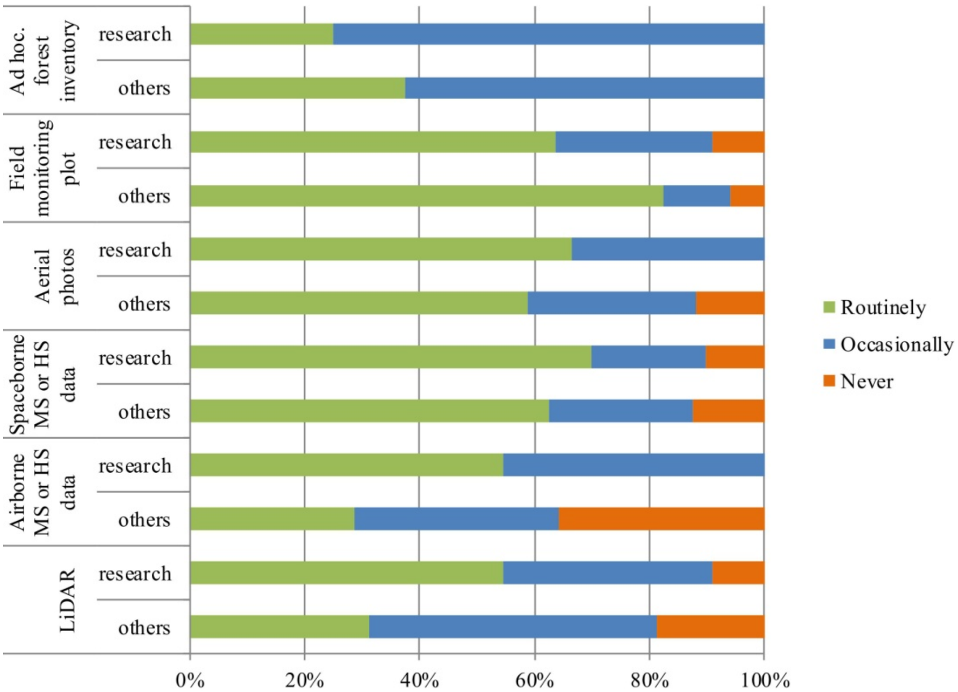

Figure 1 Currently used data sources for assessment and reporting. MS and HS stand for multispectral and hyperspectral.

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The respondents list of important attributes (Table 5) reveals some clear trends. Tree height was considered the most important attribute, followed by condition and health, crown density, and species/type mapping. These are all common forest attributes that often are obligatory in plot-based inventories (Brack 2007; McRoberts and Tomppo 2007).

Table 5 Important forest attributes listed by the respondents.

Forest attribute	1st	2nd	3rd	4th	5th	Total
Tree height	6	2	4	2		14
Forest condition and health		4	3	2	2	11
Density of tree crowns (LAI or FPC)	3	4	1	2		10
Species/type mapping	3	1	2	3	1	10
Change detection	2	2	1	2	2	9
Forest cover extent	5	2	1			8
Fire frequency and severity	1	1	3	1	2	8
Timber volumes	2	1	2			5
Vertical foliage density profile	2	1	1		1	5
Biomass/carbon	1			3	1	5
Basal area	1	2		1		4
Productivity	1	1		1	1	4
Growth stage mapping	1				2	3
Canopy disturbance		1	1		1	3
Fragmentation			2	1		3
Forest diversity, mortality, stocking, crown shape, extent of understorey vegetation	-	-	-	-	-	2
Fire risk, DEM, water stress, nativeness of non-woody vegetation, drainage mapping, canopy connectivity, understorey LAI, main substructure type (small tree,shrub,grass), fuel load	-	-	-	-	-	1

Attributes receiving one or two votes have been aggregated; only the total number of votes is shown.

Figure 2 contains results for the ranking of our list of forest attributes. The respondents assigned a level of importance to each attribute. Interpretation of the results depends on if focus is set on the *extremely important*, the *very important*, or the *important* level. With focus on the *important* level, attributes are ordered based on the percentage of votes falling into the categories of *important*, *very important* and *extremely important*. That results in aboveground biomass at the top, followed by change detection and canopy health. With a focus on the *very important*, change detection would be first, followed by canopy height and fire fuel loads. At the bottom, canopy water content, litter, and nutrient status, are the three least important according to either focus. Figure 3 compares the results for respondents divided into the three most common primary responsibility categories; biodiversity/conservation, timber production, and research. It only shows the percentage of votes at the *important* to *extremely important* levels.

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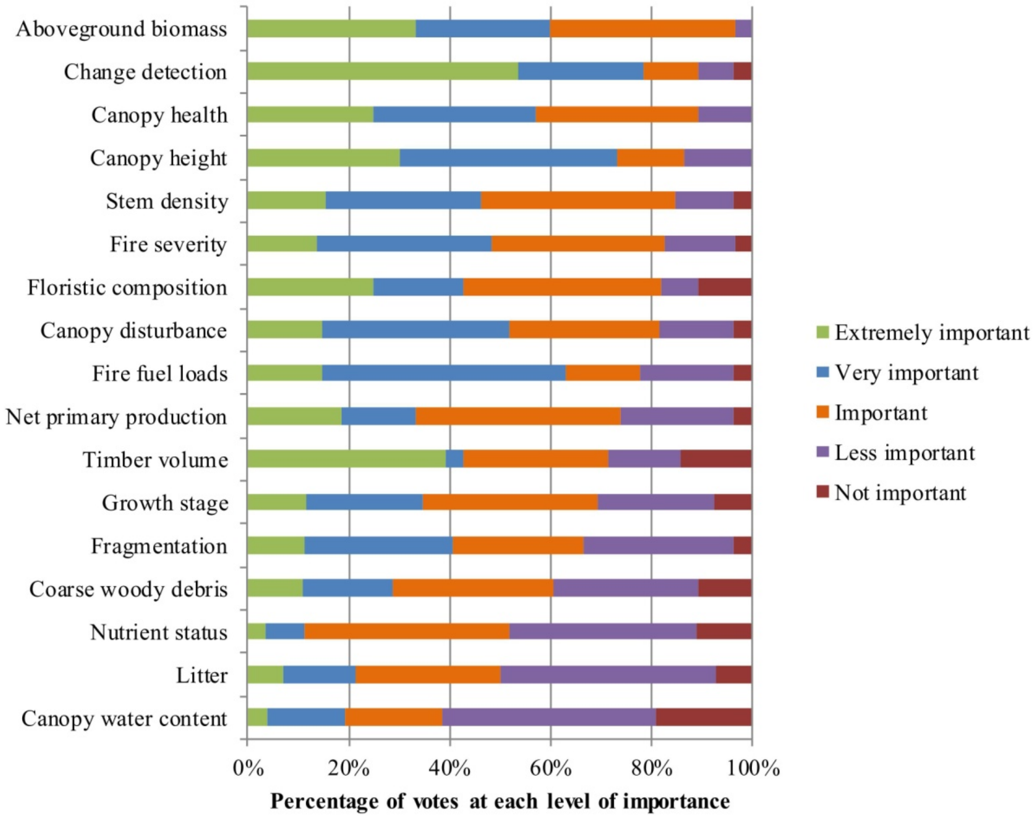

Figure 2 Ranking of forest attributes.

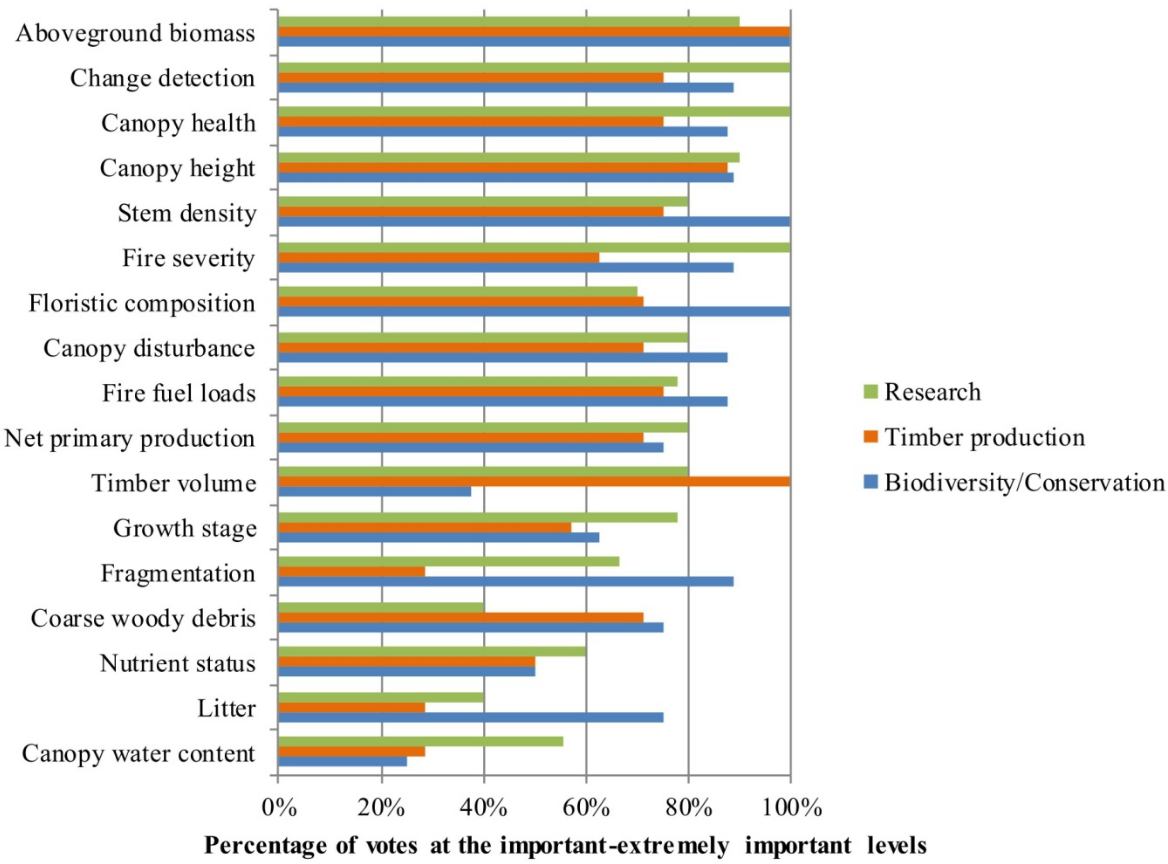

Figure 3 Comparison of attribute importance between respondent groups.

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Discussion

The results of a survey cannot be fully analysed without knowing the respondents' perspectives. In this case, they belong to a variety of different agencies with focus on different aspects of land management (Table 4). This broad range of perspectives well represents Australian land managers, and the results can be seen as an indicator of their views. The most commonly used operational methods for data capture (Figure 1) are based on mature technologies, such as spaceborne optical products and aerial photography, which have been available for decades. The results indicate that airborne multispectral/hyperspectral imagery and LiDAR are often used in research projects, but still not as widely applied in operational inventories. Their role in operational programmes is expected to grow as they become more cost-efficient and with the development of better operational routines. The common use of field monitoring plots is bound to remain as there will always be a need for validation and calibration data no matter what remote sensing technology is used.

The list of important forest attributes listed by the respondents (Table 5) is similar to the one we compiled (Figure 2). One attribute that was considered important, but was not on our list, is crown density. To summarise, the results show that the most important attributes are tree height, canopy health and condition, crown density, floristic composition, aboveground biomass, change detection, stem density, forest extent, and fire frequency/severity. Change detection is probably more accurately described as a methodology than a forest attribute. Nevertheless, its high ranking indicates a need for running monitoring programmes over longer time periods in order to detect changes. Change detection was also advocated by Brack (2007) for the case of plant biodiversity monitoring. The least important attributes include canopy water content, litter, nutrient status, and coarse woody debris. One common characteristic of these attributes, that may have influenced their low ranking, is that they are very difficult to scale up to larger areas using remote sensing. However, if they could be accurately estimated, they would be important as building blocks to get to composite attributes. The list of attributes contains many composites which require other attributes for estimation. Leaf nutrient status and water content are indicative of the canopy health status (Barry *et al.* 2008; Ustin *et al.* 2009; Chávez *et al.* 2013), and the amount of litter can be used for estimating fire fuel loads and fire hazard (Link *et al.* 2006; Gould *et al.* 2011).

The importance of attributes to different groups of respondents is shown in Figure 3. Some of the attributes, such as aboveground biomass and canopy height, appeal equally to people involved in timber production, biodiversity/conservation, and research. This reflects the close link of aboveground biomass to both timber resources and carbon stocks. The timber production group is relatively more interested in timber volumes, while the biodiversity/conservation group is relatively more concerned with stem density, floristic composition, fragmentation, and litter. Floristics and fragmentation are typical biodiversity attributes, while stem density can be indicative of growth stage and forest disturbances (Spies and Franklin 1991; Bhuyan *et al.* 2003).

Conclusions

The results of the web-based survey indicate a number of important forest attributes. The foremost are tree height, canopy health and condition, crown density, floristic composition, aboveground biomass, stem density, forest extent, and fire frequency/severity. In addition, the high ranking of change detecting highlight a need for continuous monitoring over time to detect changes and disturbances. We have shown how the attributes relate to each other; that primary attributes can inform the estimation of composite attributes such as biodiversity and canopy health. An attribute that is ranked low by the survey can thus still be important if it is informative for a highly ranked composite product.

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References

Anderson, J. E., L. C. Plourde, M. E. Martin, B. H. Braswell, M.-L. Smith, R. O. Dubayah, M. A. Hofton and J. B. Blair (2008). Integrating waveform lidar with hyperspectral imagery for inventory of a northern temperate forest. *Remote Sensing of Environment*, 112(4): 1856-1870.

Asner, G., J. Mascaro, H. Muller-Landau, G. Vieilledent, R. Vaudry, M. Rasamoelina, J. Hall and M. van Breugel (2012). A universal airborne LiDAR approach for tropical forest carbon mapping. *Oecologia*, 168(4): 1147-1160.

Barry, K. M., C. Stone and C. L. Mohammed (2008). Crown-scale evaluation of spectral indices for defoliated and discoloured eucalypts. *International journal of remote sensing*, 29(1): 47-69.

Bhuyan, P., M. Khan and R. Tripathi (2003). Tree diversity and population structure in undisturbed and human-impacted stands of tropical wet evergreen forest in Arunachal Pradesh, Eastern Himalayas, India. *Biodiversity and Conservation*, 12(8): 1753-1773.

Brack, C. L. (2007). National forest inventories and biodiversity monitoring in Australia. *Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology*, 141(1): 104-112.

* Review Paper – accepted after double-blind review.
ISBN: 978-0-9872527-1-5
Melbourne: Geospatial Sciences, RMIT 2012

Burkhart, H. E. and M. Tomé (2012). Quantifying Stand Density. Modeling Forest Trees and Stands, Springer Netherlands: 175-200.

Ceccato, P., S. Flasse, S. Tarantola, S. Jacquemoud and J.-M. Grégoire (2001). Detecting vegetation leaf water content using reflectance in the optical domain. *Remote Sensing of Environment*, 77(1): 22-33.

Chávez, R. O., J. G. P. W. Clevers, M. Herold, M. Ortiz and E. Acevedo (2013). Modelling the spectral response of the desert tree Prosopis tamarugo to water stress. *International Journal of Applied Earth Observation and Geoinformation*, 21(0): 53-65.

Clark, M. L., D. A. Roberts and D. B. Clark (2005). Hyperspectral discrimination of tropical rain forest tree species at leaf to crown scales. *Remote Sensing of Environment*, 96(3–4): 375-398.

Clark, P. J. and F. C. Evans (1954). Distance to Nearest Neighbor as a Measure of Spatial Relationships in Populations. *Ecology*, 35(4): 445-453.

Commonwealth of Australia (2012). Australia's forests at a glance 2012. Canberra, Australian Government Department of Agriculture, Fisheries and Forestry.

Coops, N. C., C. Stone, D. S. Culvenor, L. A. Chisholm and R. N. Merton (2003). Chlorophyll content in eucalypt vegetation at the leaf and canopy scales as derived from high resolution spectral data. *Tree Physiology*, 23(1): 23-31.

Franklin, J. F. and T. A. Spies (1991). Composition, function, and structure of old-growth Douglas-fir forests. USDA Forest Service, General Technical Report PNW-GTR-Pacific Northwest Research Station.

Gonzalez, J. R., M. Palahi, A. Trasobares and T. Pukkala (2006). A fire probability model for forest stands in Catalonia (north-east Spain). *Annals of Forest Science*, 63(2): 169-176.

Gould, J. S., W. Lachlan McCaw and N. Phillip Cheney (2011). Quantifying fine fuel dynamics and structure in dry eucalypt forest (Eucalyptus marginata) in Western Australia for fire management. *Forest Ecology and Management*, 262(3): 531-546.

Graham, R. T., A. E. Harvey, T. B. Jain and J. R. Tonn (1999). Effects of thinning and similar stand treatments on fire behavior in western forests. USDA Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-463.

Grove, S. and J. Meggs (2003). Coarse woody debris, biodiversity and management: a review with particular reference to Tasmanian wet eucalypt forests. *Australian Forestry*, 66(4): 258-272.

Jain, T. B. and R. T. Graham (2007). The relation between tree burn severity and forest structure in the Rocky Mountains. USDA Forest Service, General Technical Report PNW-GTR-203: 213-250.

Jonson, J. H. and D. Freudenberger (2011). Restore and sequester: estimating biomass in native Australian woodland ecosystems for their carbon-funded restoration. *Australian Journal of Botany*, 59(7): 640-653.

Kanowski, J., C. P. Catterall, G. W. Wardell-Johnson, H. Proctor and T. Reis (2003). Development of forest structure on cleared rainforest land in eastern Australia under different styles of reforestation. *Forest Ecology and Management*, 183(1–3): 265-280.

Keith, H., B. G. Mackey and D. B. Lindenmayer (2009). Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. *Proceedings of the National Academy of Sciences*, 106(28): 11635-11640.

Koch, B. (2010). Status and future of laser scanning, synthetic aperture radar and hyperspectral remote sensing data for forest biomass assessment. *ISPRS Journal of Photogrammetry and Remote Sensing*, 65(6): 581-590.

Lefsky, M. A., W. B. Cohen, D. J. Harding, G. G. Parker, S. A. Acker and S. T. Gower (2002). Lidar remote sensing of above-ground biomass in three biomes. *Global Ecology and Biogeography*, 11(5): 393-399.

Lindenmayer, D. B., C. R. Margules and D. B. Botkin (2000). Indicators of Biodiversity for Ecologically Sustainable Forest Management. *Conservation Biology*, 14(4): 941-950.

Link, S. O., C. W. Keeler, R. W. Hill and E. Hagen (2006). Bromus tectorum cover mapping and fire risk. *International Journal of Wildland Fire*, 15(1): 113-119.

Lucas, R. M., A. C. Lee and P. J. Bunting (2008). Retrieving forest biomass through integration of CASI and LiDAR data. *International journal of remote sensing*, 29(5): 1553-1577.

Maltamo, M., K. Eerikäinen, J. Pitkänen, J. Hyyppä and M. Vehmas (2004). Estimation of timber volume and stem density based on scanning laser altimetry and expected tree size distribution functions. *Remote Sensing of Environment*, 90(3): 319-330.

McElhinny, C., P. Gibbons, C. Brack and J. Bauhus (2005). Forest and woodland stand structural complexity: Its definition and measurement. *Forest Ecology and Management*, 218(1–3): 1-24.

* Review Paper – accepted after double-blind review.
ISBN: 978-0-9872527-1-5
Melbourne: Geospatial Sciences, RMIT 2012

McRoberts, R. E., W. B. Cohen, E. Næsset, S. V. Stehman and E. O. Tomppo (2010). Using remotely sensed data to construct and assess forest attribute maps and related spatial products. *Scandinavian Journal of Forest Research*, 25(4): 340-367.

McRoberts, R. E. and E. O. Tomppo (2007). Remote sensing support for national forest inventories. *Remote Sensing of Environment*, 110(4): 412-419.

Means, J. E., S. A. Acker, B. J. Fitt, M. Renslow, L. Emerson and C. J. Hendrix (2000). Predicting forest stand characteristics with airborne scanning lidar. *PE & RS- Photogrammetric Engineering & Remote Sensing*, 66(11): 1367-1371.

Montreal Process Implementation Group for Australia (2008). Australia's State of the Forests Report: Five yearly report 2008.

Næsset, E. (1997). Determination of mean tree height of forest stands using airborne laser scanner data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 52(2): 49-56.

Neumann, M. and F. Starlinger (2001). The significance of different indices for stand structure and diversity in forests. *Forest Ecology and Management*, 145(1–2): 91-106.

Pontius, J., R. Hallett and M. Martin (2005). Using AVIRIS to assess hemlock abundance and early decline in the Catskills, New York. *Remote Sensing of Environment*, 97(2): 163-173.

Richardson, J. J. and L. M. Moskal (2011). Strengths and limitations of assessing forest density and spatial configuration with aerial LiDAR. *Remote Sensing of Environment*, 115(10): 2640-2651.

Rossini, M., C. Panigada, M. Meroni and R. Colombo (2006). Assessment of oak forest condition based on leaf biochemical variables and chlorophyll fluorescence. *Tree Physiology*, 26(11): 1487-1496.

Solberg, S., E. Næsset, K. H. Hanssen and E. Christiansen (2006). Mapping defoliation during a severe insect attack on Scots pine using airborne laser scanning. *Remote Sensing of Environment*, 102(3–4): 364-376.

Spies, T. A. and J. F. Franklin (1991). The structure of natural young, mature, and old-growth Douglas-fir forests in Oregon and Washington. USDA Forest Service, Pacific Northwest Research Station, General technical report PNW-GTR-85**:** 91-109.

Stokland, J. N. (2001). The coarse woody debris profile: an archive of recent forest history and an important biodiversity indicator. *Ecological Bulletins*: 71-83.

Stone, C. and A. Haywood (2006). Assessing canopy health of native eucalypt forests. *Ecological Management & Restoration*, 7: S24-S30.

Stone, C., T. Wardlaw, R. Floyd, A. Carnegie, R. Wylie and D. De Little (2003). Harmonisation of methods for the assessment and reporting of forest health in Australia–a starting point. *Australian Forestry*, 66(4): 233-246.

Tanskanen, H., A. Venäläinen, P. Puttonen and A. Granström (2005). Impact of stand structure on surface fire ignition potential in Picea abies and Pinus sylvestris forests in southern Finland. *Canadian Journal of Forest Research*, 35(2): 410-420.

Tonolli, S., M. Dalponte, M. Neteler, M. Rodeghiero, L. Vescovo and D. Gianelle (2011). Fusion of airborne LiDAR and satellite multispectral data for the estimation of timber volume in the Southern Alps. *Remote Sensing of Environment*, 115(10): 2486-2498.

Ustin, S. L., A. A. Gitelson, S. Jacquemoud, M. Schaepman, G. P. Asner, J. A. Gamon and P. Zarco-Tejada (2009). Retrieval of foliar information about plant pigment systems from high resolution spectroscopy. *Remote Sensing of Environment*, 113, Supplement 1(0): S67-S77.

Ustin, S. L., D. A. Roberts, J. Pinzón, S. Jacquemoud, M. Gardner, G. Scheer, C. M. Castañeda and A. Palacios-Orueta (1998). Estimating Canopy Water Content of Chaparral Shrubs Using Optical Methods. *Remote Sensing of Environment*, 65(3): 280-291.

Van Den Meersschaut, D. and K. Vandekerkhove (2000). Development of a stand-scale forest biodiversity index based on the state forest inventory. Integrated tools for natural resources inventories in the 21st century. Gen. Tech. Rep. NC-212. St. Paul, MN: USDA Forest Service, North Central Forest Experiment Station**:** 340-350.

Wimberly, M. C. and T. A. Spies (2001). Influences of environment and disturbance on forest patterns in coastal Oregon watersheds. *Ecology*, 82(5): 1443-1459.

Woinarski, J. C. Z., J. Risler and L. Kean (2004). Response of vegetation and vertebrate fauna to 23 years of fire exclusion in a tropical Eucalyptus open forest, Northern Territory, Australia. *Austral Ecology*, 29(2): 156-176.

Ziegler, S. S. (2000). A comparison of structural characteristics between old-growth and postfire second-growth hemlock–hardwood forests in Adirondack Park, New York, U. S. A. *Global Ecology and Biogeography*, 9(5): 373-389.

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