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Chapter 5

Harnessing landholder's knowledge for efficient environmental monitoring, accounting, and management for new environmental markets: Lessons from plantation forestry carbon sequestration in Western Australia.

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Abstract

Leveraging limited environmental monitoring and management funding using landholder knowledge and capacity can reduce total costs of implementing plantation forestry environmental market mechanisms by both reducing duplication and enhancing on-ground activities to assimilate environmental and production system decisionmaking. This articlechapter? explores the integration of high accuracy on-site vegetative and ecological methods and metrics (on-site verification, allometrics, expansion factors, carbon factors, root-to-shoot ratios, etc.) into landscape and macro-scale plantation carbon and land monitoring models to assist the development of innovative ecosystem service markets derived from forestry plantation and carbon sequestration developments. Several limitations of current methods and policies are outlined, requiring primarily information tools and communication pathways to redress, opening the possibility for formally capturing lifetimes of local landholder knowledge of forestry land use and environmental system changes. This work suggests parallel advancements of on-site landholder and remote land monitoring and management has the potential to achieve a multitude of efficiencies. These include: cost-effective skilled environmental management jobs in regional and remote areas; streamlined administration and research expenditures for on-site environmental monitoring and supporting costs (transport, accommodation, etc.); locally appropriate conservation activities sustained over time, and; direct communication between landholders, researchers, and policymakers.

Keywords: Land; biomass; allometry; modelling; policy; plantation forestry.

Introduction

Emerging climate change, carbon (C), biodiversity, and water markets bring to attention the multitude of functions that ecological systems perform (Fromm, 2000; Griffiths et al., 2000; Nunes & van den Bergh, 2001; Australian Greenhouse Office, 2006). While afforestration, reforestation, or revegetation seem to offer a simple prescriptive solution to achieve environmental and climate change objectives from a policymakers perspective, those on the land must manage a range of complex biological processes that compete for limited resources (Van Vreeswyk et al., 2004). By aiming to simultaneously improve land productivity, biodiversity, water quality (etc.), and mitigate greenhouse gas (GHG) emissions, progress can be made where transdisciplinary government and landholder objectives overlap (Antheaume, 2004).

On-site physical ecological accounting by inhabitants at the landscape level provide calibration and verification of satellite monitoring and model assessment methods, enhance quantitative analyses of vegetative physical characteristics, and offer first-hand multigenerational knowledge of the land (Landsberg

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& Crowley, 2004; Balilla et al., 2012). Landholder on-site accounting presents a relatively simple method to monitor changes in complex ecological functions that bolster effective environmental market development. For example, biomass, C, surface or groundwater, vapour, heat, or endemic species (etc.) fluxes may be used as proxy indicators that markets can deem to represent functional ecosystem changes at the landscape level. However, such deeming mechanisms may be imprecise, exhibit many approximations, assumptions, and conceal uncertainty in complex biological responses to change, and high uncertainties in real values generally result in lower market values for deeming activities and products (McHenry, 2009b, 2010, 2011). Nonetheless, the two crucial points in relation to deeming are essentially economic in nature: the net value of deeming market participation to private landholders, and the administrative efficiency of 'soft' approaches that capture landholder capacity to protect public goods at the landscape scale. Essentially, deeming may be an imperfect mechanism, but it need not be inaccurate or an expensive market mechanism to tip the balance towards better land use policy outcomes.

In terms of new C markets, to effectively engage landholders to invest in changing the productive balance of their land requires knowledge of the sequestration potential of specific species and the likely costs and benefits to their existing production systems (McHenry, 2009a). New suites of tree species will influence the lands groundwater tables, stream flows, weed and fauna management regimes, fire control measures, and the landowner's economic situation (Clifton et al., 2007). Planning for new complex activities requires a very high resolution of often site-specific biological, geological, sociological, and economic information. While larger regional or landscape scale site models can broadly inform land use change (LUC) policymakers and researchers regionally, in practice there is often little reciprocal communication with those who actively manage and live on the land. Such inhabitants will likely be able to enhance the appropriateness of input data, assumptions and refine resulting policy outputs and conclusions.

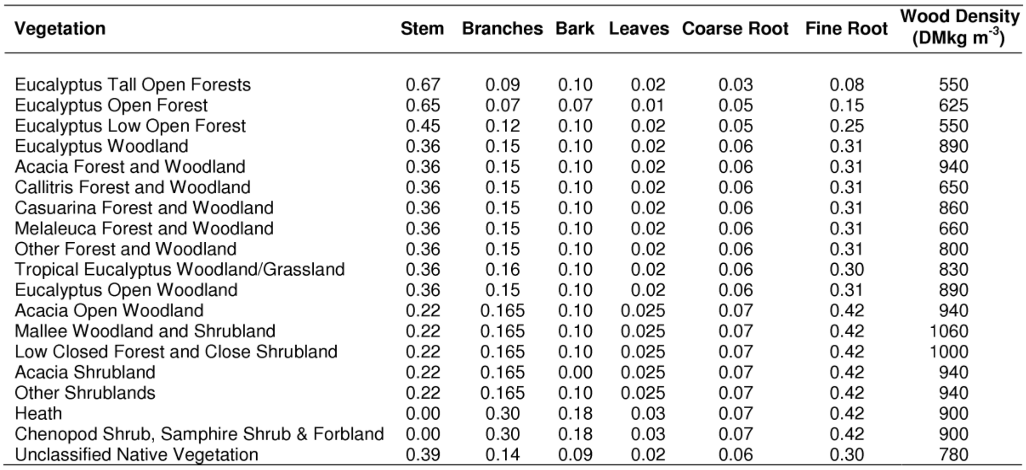
To sustainably operate at the landscape scale, landholders require very high resolution and extremely reliable information with a focus on seasonal fluxes and environmental extremes, rather than annually averaged data. Of particular interest to landholders are the maintenance and thresholds of critical systems that sustain productivity, and often use specific indicator species characteristics to monitor biological responses to seasonal and annual landscape change. Thus seasonally differentiated functional ecosystem change datasets are a fundamentally appropriate foundation for researchers and policymakers to develop and maintain (Landsberg & Crowley, 2004; Stoneham, 2009). While potentially more costly initially, information systems and models with multiple utilities will have a greater reciprocal value to land managers, government planners, and industry security generally in periods of increased climatic variability than much of the annually averaged data currently generated and used. Market mechanisms can be harnessed to attract new investment to either directly or indirectly assist the ability of governments to initiate the collaborative development of monitoring and verification activities. However, investors will require certainty a priori (Stoneham, 2009).

New markets will likely create new land ownership rights to maintain investor certainty. Thus, landholders will also require long-term certainty regarding possible claims of rights to the land from governments, ecological product holders, and how a diversified ownership structure may influence their livelihood. In 2003, the Western Australian Parliament passed the Carbon Rights Act 2003, which gave landowners a statutory basis to register, and trade the C rights earned since 1 January 1990 as a separate interest in the land (The Parliament of Western Australia, 2003). At present, what transpires on the land after C trading is dependent on the legal obligations imposed under transfer of such rights, which are in-turn dependent on each particular trading mechanism design. New markets will likely require similar new property rights, and will thus require a similar legislative basis, although the monitoring and verification regimes will likely require much additional but complimentary ecological input data. While quality datasets enable the development of stable and sustained markets with a high level of transparency, such datasets require an additional level of resolution, transparency, and efficiency in combining regional models and on-site verification than is available today. However, analogous developments have enabled the development of C markets, which with augmentation, may be a suitable foundation for various ecological markets.

The Interface Between C Models and On-Site Verification

The development of the Australian National Carbon Accounting System (NCAS) was required to decrease uncertainty, improve transparency, and improve verification of national land use, land-use change, and forestry (LULUCF) assets and fluxes under the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol commitments (Australian Greenhouse Office, 1999b, 1999a; Turner et al., 1999; Polglase et al., 2000; Snowdon et al., 2000; Richards, 2001; Australian Greenhouse Office, 2002; Furby, 2002; Furby & Woodgate, 2002; Paul et al., 2002; Richards et al., 2002; Booth et al., 2003; Australian Greenhouse Office, 2005b, 2005a). The NCAS methodology was developed to be more rigorous than the minimum requirements of the Intergovernmental Panel on Climate Change (IPCC) guidelines for forest C monitoring. The IPCC guidelines were based on forests of trees with the potential to reach a minimum of 2 metres in height at maturity, a tree crown cover (or equivalent) of more than 20% and a minimum area of 0.2 ha (Australian Greenhouse Office, 2002, 2005b). To quantify the total amount of C in woody tissue both the volume and density of tissue must be known (Ilic et al., 2000). (See Table 1 for an example of vegetative class partitioning and density data).

Table 1. Partitioning of biomass and wood density values by major vegetation group class. Source: (Australian Greenhouse Office, 2002).



Vegetation	Stem	Branches	Bark	Leaves	Coarse Root	Fine Root	Wood Density (DMkg m^{-3})
Eucalyptus Tall Open Forests	0.67	0.09	0.10	0.02	0.03	0.08	550
Eucalyptus Open Forest	0.65	0.07	0.07	0.01	0.05	0.15	625
Eucalyptus Low Open Forest	0.45	0.12	0.10	0.02	0.05	0.25	550
Eucalyptus Woodland	0.36	0.15	0.10	0.02	0.06	0.31	890
Acacia Forest and Woodland	0.36	0.15	0.10	0.02	0.06	0.31	940
Callitris Forest and Woodland	0.36	0.15	0.10	0.02	0.06	0.31	650
Casuarina Forest and Woodland	0.36	0.15	0.10	0.02	0.06	0.31	860
Melaleuca Forest and Woodland	0.36	0.15	0.10	0.02	0.06	0.31	660
Other Forest and Woodland	0.36	0.15	0.10	0.02	0.06	0.31	800
Tropical Eucalyptus Woodland/Grassland	0.36	0.16	0.10	0.02	0.06	0.30	830
Eucalyptus Open Woodland	0.36	0.15	0.10	0.02	0.06	0.31	890
Acacia Open Woodland	0.22	0.165	0.10	0.025	0.07	0.42	940
Mallee Woodland and Shrubland	0.22	0.165	0.10	0.025	0.07	0.42	1060
Low Closed Forest and Close Shrubland	0.22	0.165	0.10	0.025	0.07	0.42	1000
Acacia Shrubland	0.22	0.165	0.00	0.025	0.07	0.42	940
Other Shrublands	0.22	0.165	0.10	0.025	0.07	0.42	940
Heath	0.00	0.30	0.18	0.03	0.07	0.42	900
Chenopod Shrub, Samphire Shrub & Forbland	0.00	0.30	0.18	0.03	0.07	0.42	900
Unclassified Native Vegetation	0.39	0.14	0.09	0.02	0.06	0.30	780

The NCAS is based on resource inventories, site specific studies, multi-temporal remote sensing, and sequential modelling land cover change, LUC, soil type, forest type, management, climate, biomass growth, and litter inputs to scenario projections of the C balance of LUC projects, or at the national level (Booth et al., 2003; Australian Greenhouse Office, 2005b). The NCAS includes C quantification verification, which is based on the Full Carbon Accounting Model (FullCAM), that provides a 25 m grid resolution of C fluxes over monthly time steps (Richards, 2001; Australian Greenhouse Office, 2002; Booth et al., 2003; Australian Greenhouse Office, 2005b, 2006). FullCAM is capable of C accounting for afforestation, reforestation, revegetation, and deforestation, as well as agroforestry systems, and is comprised of a combination of Excel-based accounting tools that model biological processes. Many of the model parameters are user-defined to reflect land management decisions and rates of C transfer between pools, or the atmosphere (Richards, 2001). The various modelled biological processes include land cover change, land use and management, climate input, crop growth and plant parameters, biomass stock and growth incremements, tree parameters, forest parameters, soil C, and the model framework (Australian Greenhouse Office, 2002, 2005b). The five sub-models incorporated into FullCAM are 3-PG (forest physiological growth model), CAMFor (forest C accounting model), CAMAg (cropping and grazing C accounting model), GENDEC (microbial decomposition model), and the Roth-C (soil C model) (Richards, 2001; Australian Greenhouse Office, 2002). The CAMFor component assists C accounting and projections by calculating the C flows associated with forest and tree stand changes, and also any wood product harvesting activities (Brack et al., 2002; Brack & Richards, 2002). CAMFor converts annual changes in stem wood using parametrics that approximate annual changes in tree components alongside C content. The parametrics of importance are stem wood density and the variation of other tree components relative to the stem, which vary with species, age, size, and on-site conditions (Booth et al., 2003). Growth in the bark, branch, leaf, twig and root pools are modelled as an age dependent increase relative to stem growth (Brack & Richards, 2002). FullCAM incorporates these and other biological processes in relation to biogeographic information in the FullCAM database (Booth et al., 2003).

To generate emissions and removals estimates for reforestation projects, a component of the NCAS, the Carbon Accounting Toolbox (NCAT) was collaboratively developed by the Australian Greenhouse Office, CSIRO, and the Australian National University. NCAT uses the same data and models as the NCAS to generate net GHG removals and emission estimates without requiring input data relating to stem volume and wood density. Thus, forest entities using NCAT only require forest data such as tree species, years of establishment, thinning measures, rotation intervals and any fertiliser applications as input data. While the Australian Government does not yet prescribe the use of the NCAT, they do recommend its use for forestry C emission and removal modelling to utilise the continually updated climate, management activity, remote sensing, soil data, and forest type databases (Department of Climate Change, 2008). Crucially, much of this updating incorporates on-site assessment, as it is important that local data sets are not solely reliant on satellite imagery as to limit interpretive errors. The on-site data greatly increases image interpretation and validation of remote sensing results (Furby & Woodgate, 2002; Clifton et al., 2007).

On-site Verification to Improve Model Effectiveness

Some on-site measurement methods are expensive, but accurate, while others are inexpensive and less accurate. Remote sensing is one relatively inaccurate method, but has the advantage of being inexpensive (Richards et al., 2002). Physiological models based on remote sensing require relatively expensive field calibration from a network of quality audited permanent plots (Australian Greenhouse Office, 1999a; Turner et al., 1999; Richards, 2001; Richards et al., 2002). Researching economically efficient means to calibrate and verify models through longitudinally maintained site-specific plot data sets is an important area for policymakers to facilitate. The temporal distinction between calibration and verification practices and data enable a longer term comprehension of changes in ecosystems from historically continuous data. One serious gap in environmental inventories for verification and calibration purposes relates to the dearth of private land information held in the public sphere. This restricts the reliability of the increasingly important land use policy (Richards, 2001).

Development of systems such as the NCAS are undertaken recognising the imperfect nature of the input data and the output. The system focuses on functional aggregated accuracy and objectivity rather than attempt to pursue an ultimate level of precision of biomass growth (Australian Greenhouse Office, 2002). The net primary productivity (NPP) of forests is the rate at which solar energy is converted to biomass, and its quantification is essentially the objective of such models. Destructive sampling is one method of determining NPP, and while it is suitable for individual plots of grass and shrub vegetation, it is rarely used for forest ecosystems (Snowdon et al., 2002; Kesteven et al., 2004). There are two basic methods for destructively estimating aboveground biomass of individual trees: the complete harvest method, and; the partial harvest methods (Snowdon et al., 2002). However, determining the biomass and C in standing, unharvested trees is accomplished by using calculations that model the tree components such as stems, crowns, roots and tops for different sizes, ages and tree spacing (Australian Greenhouse Office, 1999a; Ritzon & Sochacki, 2002; Bi et al., 2004). Using easily measured tree characteristics to estimate tree biomass is called allometry, and thousands of allometric equations for individual species in specific areas have been developed using slightly different methods (Australian Greenhouse Office, 1999a; Eamus et al., 2000; Richards et al., 2002; Specht & West, 2003; Bi et al., 2004).

Allometrics and Expansion Factors: Utility and Limitations for New Markets

Allometric equations are an important technique to estimate tree and forest biomass and sufficient information is available to estimate growth rates for forests (Australian Greenhouse Office, 1999a; Turner et al., 1999; Richards et al., 2002). Relatively few allometric equations are required to adequately describe the aboveground biomass of some vegetation types, especially where one or two species dominate site basal area (the cross sectional area of trees in a forest in m^2 ha^{-1}) (Australian Greenhouse Office, 1999a; Richards et al., 2002). On-site sampling of basal area tree height, and volume are currently used to refine NCAS estimates of mature forest and regrowth of various ages (Australian Greenhouse Office, 1999a, 2006). Basal area is often recommended as a standard measure for allometric equations as it was often the only forestry variable recorded (Richards et al., 2002). Aboveground biomass can be estimated from stand basal areas using ratios established for major Australian forest types (Australian Greenhouse Office, 2006). However, basal area only allometric equations are less useful than those that incorporate diameter at breast height (DBH) measurement (Richards et al., 2002). Stem diameter can include DBH, or DBHOB (diameter at breast height over bark), which are generally 130 cm from the ground unless stated otherwise (Brokaw & Thompson, 2000; Eamus et al., 2000; Keith et al., 2000; Snowdon et al., 2002; Zianis & Mancuccini, 2004). If possible all diameter measurements should be undertaken for both over and under the bark. This can either be undertaken by removing the bark, or using a bark depth gauge to estimate the under bark diameter. One use of measuring stem diameters both over and under the bark is to estimate dry weight of dead trees and also to determine biomass information about the bark itself. It is possible to get a good indication (generally within 2% difference) of stem bark thickness by measuring only two opposite points on the stem. Other common stem measurements are diameters at 10 cm (d_{10}) and 30 cm (d_{30}), which are used for small trees or shrubs prone to forking. When there is more than one stem on the sample tree, calculating the diameter of a circle of area equal to the sum of the cross-section areas of all stems at the same height is known as the diameter equivalent (d_e) (Snowdon et al., 2002). Average biomass estimates across a wide range of sites can be adequately estimated when using two variables, such as height and stem diameter for specific species and their sizes (Snowdon et al., 2000). Tree height estimation on standing trees commonly use trigonometric or hypsometers at right angles from any lean with two measurements from the opposite side of the tree (Snowdon et al., 2002).

A study by Ritzon and Sochacki (2002) developed a model for predicting the biomass and C for *Pinus pinaster* (Maritime pine) in the southwest of WA. This included destructive sampling of trees aged between 1 and 47 years to determine dry matter biomass and C content to develop allometric equations. Similar to comparable research, the study found that the aboveground biomass of the tree contained very close to 50% C and the belowground tree mass C content was around 48%, and that using more than one measurement provided the most reliable allometric estimations (Ritzon & Sochacki, 2002). They developed equations that predicted biomass and C for each component of the Maritime pines adequate for various management practices, such as pruned for sawlogs, unpruned single paddock trees, or grown in a windbreak.

The fundamental importance of biomass estimation for C and other ecological markets necessitates a comprehensive suite of predictive equations for landscapes and species (Australian Greenhouse Office, 1999a). It is possible to find simple linear allometric equations of the form $Y = a + bD$, where *a* and *b* are the scaling coefficients, Y the total aboveground tree dry biomass or tree height, and D is the DBH (See Table 2 and Figure 1). However, the most commonly used form for biomass studies is $M = aD^b$ (Zianis & Mancuccini, 2004). The variability of M is largely related to variability of D measurement, while values of *a* and *b* vary with species, stand age, site, climate, and stand density. As the relationship between M and D corresponds well to a power function, the raw data is usually transformed logarithmically (Zianis & Mancuccini, 2004). (See Table 3 for a list of logarithmically transformed linear allometric equations). Coefficients *a* and *b* are usually determined by least-square regression of log-transformed data for DBH, and M measured from destructive sampling (Eamus et al., 2000; Zianis & Mancuccini, 2004).

Table 2. Linear regressions of the form $Y = a + bD$ tables to estimate physical attributes of 10 four year old *Eucalyptus astringens* (Brown Mallet) trees using DBHOB measurements. Source: (Eamus et al., 2000).

Y Value	D Value[1]	a	b	R^2	P Value
Stem (kg)	DBHOB (m)	-2.5999	206.16	0.84	<0.0001
Height (m)	DBHOB (m)	1.6300	70.924	0.87	<0.0001
Branches and fruit (kg)	DBHOB (m)	-0.6967	65.47	0.69	<0.0018
Leaves (kg)	DBHOB (m)	-0.4723	82.01	0.77	<0.0005
Total biomass (kg)	DBHOB (m)	-3.770	353.65	0.83	<0.0001

[1] DBHOB is diameter at breast height over bark.

Unfortunately, there are fundamental issues with much of the available allometric data and collection methods. Uncorrected estimates of biomass derived from least squares regression on logarithmically transformed data should not be used to estimate biomass as they seriously underestimate biomass without correction factors (Eamus et al., 2000). If available, correction factors allows landholders to accurately quantify tree biomass from allometric equations by measuring the relevant variables in the equations, such as the DBH (Eamus et al., 2000; Bi et al., 2004). However, without correction factors biomass is likely to be underestimated due to the DBH being relatively large and being skewed by the antilogarithmic transformation[1] (Eamus et al., 2000). The primary untransformed data is of much greater utility to landholders and new markets, although very little original data exists, and/or is available. Furthermore, allometric equations technically only apply to the forest stand where they were derived, and equations will likely be unsuitable outside of the tree species, tree size class, and the region of which they were obtained (Snowdon et al., 2000; Richards et al., 2002). Despite these fundamental limitations, the primary source of error with available biomass estimation equations derives from regression analyses. Statistical comparisons

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[1] Research by Eamus et al. (2000) includes a useful overview of allometric correction factors.

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and the combination of equations is constrained by a lack of standard mathematical form, differences in independent variables, lack of statistical transformation information, and deficiency in details of the original data (Australian Greenhouse Office, 1999a).

For larger areas of trees there are a range of what are called 'expansion factors', which are used with sample results to more accurately determine biomass and sequestration of larger numbers of trees in accordance with NCAS protocols (Snowdon et al., 2002). Expansion data assist accurate useful for modelling when the location and volumes are known, and must be of sufficient detail, which may impinge on commercial sensitivities (Australian Greenhouse Office, 1999a). Expansion factors vary according to species, canopy cover, region (etc.) (Australian Greenhouse Office, 1999a; Furby, 2002). There are also differences between commercial forest and unmanaged forests in terms of allometric regression expansion factors (Australian Greenhouse Office, 1999b). These differences in land use should be reflected by differences in allometric and expansion factor data. However, the main source of error in upscaling biomass estimates using expansion factors relates to the number and adequacy of sampled representative plots and the level of natural heterogeneity of particular forest species (Australian Greenhouse Office, 1999a). Conversion of measurements to total forest biomass requires wood density measurements and expansion factors that account for the stem as a proportion of the total tree including stem, bark, branches, twigs, leaves and root data (Australian Greenhouse Office, 1999a; Keith et al., 2000). Non-destructive sampling methods at a site commonly entails removing 0.12 cm increment core from 110 cm aboveground to ascertain whole tree density. The assessment of wood density also requires the recording of the location, altitude, age, and species of the tree, the height of the tree and sample points, diameter over bark at the sampling point, compass direction of the sample, median and seasonal distribution of rainfall, soil type, and a measure of site quality (Ilic et al., 2000). Such details are rarely available, especially in primary form, free from statistical transformation.

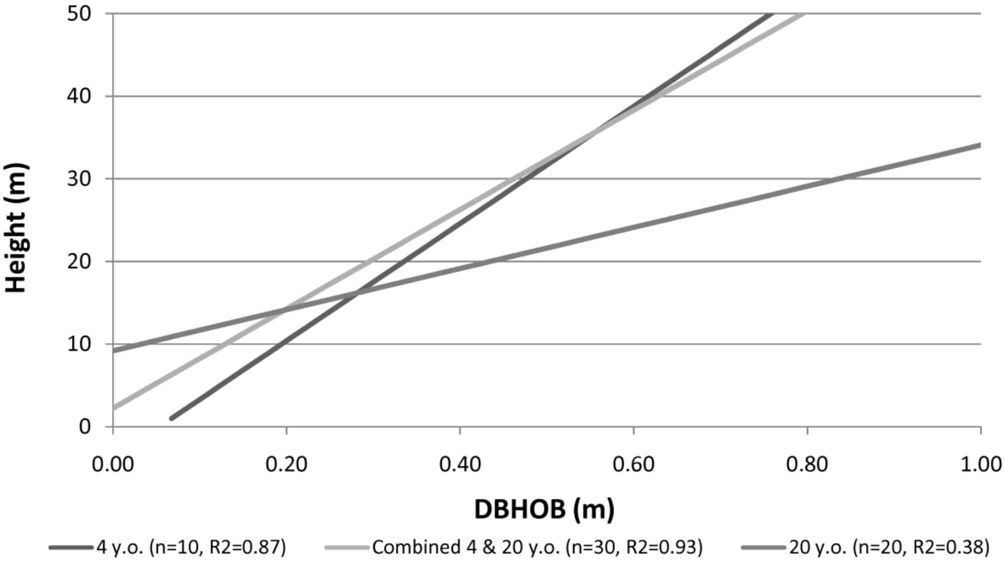

Figure 1. Linear regression functions derived from 30 *Eucalyptus astringens* (Brown Mallet) trees of four and twenty years of age to approximate height (m) from DBHOB (m).

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Table 3. Selected available regression analyses of the form *ln*(M) = aln*(DBH)+b of tree species grown in WA. Source: (Eamus et al., 2000).**

Name	Common Name	DBH Details[1]	DBH Range	n	a	b	R^2	Author(s)
Eucalyptus marginata	Jarrah	AG (kg) DBH (cm)	-	10	2.84	-3.680	0.994	Hingston et al. (1981)
Corymbia calophylla	Marri	AG (kg) DBH (cm)	-	10	2.74	-3.370	0.982	Hingston et al. (1981)
Banksia grandis	Bull Banksia	AG (kg) DBH (cm)	-	16	2.50	-2.260	0.963	Hingston et al. (1981)
Eucalyptus diversicolor	Karri	DBH (cm) at 30cm height	-	-	2.107	4.501	0.99	Grove (1998)
Eucalyptus diversicolor	Karri	DBH (cm) at 130cm height	-	-	2.128	5.146	0.99	Grove (1998)
Bossiaea laidlawiana	Waterbush subsp.	DBH (cm) at 30cm height	-	-	2.70	4.998	0.99	Grove (1998)
Bossiaea laidlawiana	Waterbush subsp.	DBH (cm) at 130cm height	-	-	2.814	4.268	0.99	Grove (1998)
Trymalium spathulatum	Karri Hazel	DBH (cm) at 30cm height	-	-	2.722	4.284	0.99	Grove (1998)
Trymalium spathulatum	Karri Hazel	DBH (cm) at 30cm height	-	-	2.795	3.849	0.99	Grove (1998)
Chlorilaena quercifolia	Karri Oak	DBH (cm) at 3cm height	-	-	2.665	4.187	0.96	Grove (1998)
Lasiopetalum floribundum	Free Flowering L.	DBH (cm) at 3cm height	-	-	2.663	4.267	0.98	Grove (1998)
Pimelea clavata	Rope Banjine	DBH (cm) at 3cm height	-	-	3.146	3.027	0.98	Grove (1998)
Acacia pulchella	Prickly Moses	DBH (cm) at 3cm height	-	-	2.992	4.445	0.97	Grove (1998)
Hibbertia cuneiformis	Cutleaf Hibbertia	DBH (cm) at 3cm height	-	-	2.681	3.591	0.93	Grove (1998)
Corymbia maculata site A	Spotted Gum	AG (kg) DBHOB (cm)	2–24.5	10	2.47	-2.51	0.95	Ward and Pickersgill (1985)
Corymbia maculata site B	Spotted Gum	A&BG (kg) DBHOB (cm)	2.0–11.5	11	1.87	-1.1	0.98	Ward and Pickersgill (1985)
Eucalyptus resinifera site A	Red Mahogany	AG (kg) DBHOB (cm)	-	8	2.44	-2.54	0.97	Ward and Pickersgill (1985)
Eucalyptus resinifera site B	Red Mahogany	DBH (cm)	2.0-11.5	10	1.74	-1.12	0.98	Ward and Pickersgill (1985)
Corymbia calophylla site A	Marri	DBH (cm)	-	-	2.04	-1.54	0.99	Ward and Pickersgill (1985)
Corymbia calophylla site B	Marri	DBH (cm)	-	-	1.64	-0.92	0.89	Ward and Pickersgill (1985)

[1] AG is aboveground, A&BG is above and belowground, DBH is diameter at breast height, DBHOB is diameter at breast height over bark.

Carbon Content and Complexities in Belowground Biomass Estimation

Biomass estimates are converted to C by applying C factors, and in contrast to allometrics and expansion factors, turn out to be remarkably consistent between species and regions (Australian Greenhouse Office, 2006). (Table 4 shows general C content and turnover rates). Australian research by Gifford (2000a) found that overall C contents of all tree tissues and species was 50%, while leaves exhibit slightly higher C content of 52.8%, and leaf litter C content was 54.3%. Gifford recommended for when a single %C value is required to represent all aboveground components of all species, a value of 50±2% be used. When leaves were analysed separately a value of 53±2% be adopted, and for Australian native species, a value of 50±2% for woody components is appropriate. Deep wood near the centre of the trunk exhibited around 2% higher C contents than sapwood due to lower mineral contents (Gifford, 2000a). Gifford (2000b) also obtained an averaged value for the C content of coarse wood root of 49±1%, based on an analysis of 23 species. The range of these 23 species was 46.7 to 51.2%. When a continental value for forest roots including fine roots, 48±2% is suggested, and when a single figure is required that represents the C content of all woody components above and belowground (including branches and coarse roots), 49±2% is suggested. Significantly, there is often less variability between tree species than between tissues (Gifford, 2000b). While carbon factors themselves add little uncertainty to C estimates, the errors of biomass carried through assessments remain the greatest source of uncertainty.

Table 4. Carbon contents and annual turnover rates of tree components. Source: (Eamus et al., 2000; Australian Greenhouse Office, 2002).

Tree Component	Dry Matter Carbon Content	Component Turnover Rate
Leaves and Twigs	0.52	0.0470
Branches	0.47	0.0056
Bark	0.49	0.0083
Stem	0.50	-
Coarse Roots	0.50	0.0560
Fine Roots	0.48	0.1042

Biomass estimation through allometric relationships can be complicated by seasonal and annual variability in NPP, unique underground vegetative structures, harvesting, fire, or unusual environmental conditions (Turner et al., 1999). In mallee vegetation (low growing, multi-stemmed Eucalypt species) individual lignotubers may be very large and coppicing or fire can stimulate lignotuber growth as the tissues grow and the lignotuber merges with the stem base (Kalin Arroyo et al., 1995; Snowdon et al., 2002). In southern Australia, the soil water holding capacity over the period in summer and autumn (December to May), often determines the growth and survival of trees (Hingston et al., 1998). In water limited regions the relationship between age and biomass may not be strong due to the opportunistic growth rate of vegetation in the more arid systems (Turner et al., 1999; Van Vreeswyk et al., 2004). As root biomass growth patterns generally reflect water availability, sampling for minimum root biomass should correspond to the driest period of the year and vice versa (Snowdon et al., 2002). Species and regional variability will undoubtedly require on-site sampling to refine estimations for many forest and ecological market requirements. This is especially so in relation to belowground biomass, often estimated using 'root-to-shoot' (RS) ratios (Australian Greenhouse Office, 1999a; Turner et al., 1999; Richards et al., 2002).

RS ratios are used to estimate belowground biomass from aboveground data (Australian Greenhouse Office, 2006). The availability and resolution of appropriate RS ratio allometric equations and expansion factors will determine both the costs and the accuracy of total biomass measurement and estimation.

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Unfortunately, there is variable availability of allometrics and expansion factor details for RS ratios and for larger trees over 50 cm DBH (Australian Greenhouse Office, 1999a; Richards et al., 2002). Australian native species are renowned for their high variability of RS ratios within and between forest types, which is attributable to species, age, soil and climate (etc.) conditions (Snowdon et al., 2000; Richards et al., 2002). Temporal variations in fine root biomass for *Eucalyptus marginata* (Jarrah) forests in Western Australia can vary up to four-fold between summer and winter months, which is around 20% of the total root biomass (McKenzie et al., 2000; Snowdon et al., 2002). This complexity is also compounded by the relationship between above and belowground biomass from fires, coppicing, and seasonal variation (Snowdon et al., 2002).

Management Complexities and Opportunities for Integrating Local Knowledge

There is also a paucity of data regarding Australian tree harvest characteristics in privately managed forests and environmental plantings. As fuelwood is often sourced from state forests, obtaining data regarding these activities can only occur at the retail and landholder level (Australian Greenhouse Office, 1999a). These woody C flows into various product classes and physical residence times needs be quantified, as the total net Australian pool of C sequestered as wood in the national housing stock alone is estimated to be around 10 MtC (Australian Greenhouse Office, 1999a; Jaakko Poyry Consulting, 2000). As policymakers seek to refine the accuracy and precision of national C accounting, there is likely to be a growing need for reliable data of this nature, and its collection will require the involvement of both researchers and local landholders (Australian Greenhouse Office, 1999a). Regional information of this nature can also be used to calculate the energy available for use in the expanding renewable energy markets in relation to woodheater demand, for cofiring in conventional generators, or the growing market for small bioenergy units cogenerating useful electricity and heat in regional areas (McHenry, 2009a).

In relation to environmental markets attributed to vegetative management, identifying the timing and implementation of any land use activity will likely require very detailed biological modelling, especially when concerning fire management. This quantification will require both the concurrent agents of change, and the separated impact of change to be determined (Richards, 2001). However, modelling data in inappropriately high resolutions may presume a sense of false precision for market participants, and a balance between market value, transparency, and practicality should evolve (Australian Greenhouse Office, 1999a).The most likely form that individual landholders will be able to take part in future environmental markets will be through 'pooling'. In a similar manner to supply market quantities of niche products, or more recently, C pooling involves combining a number of small registered areas in order to generate sufficient marketable product volume to obtain a positive return by sharing costs of technical measurement, certification and marketing of the credits (The CRC for Greenhouse Accounting & Tony Beck Consulting Services Pty Ltd, 2003; McHenry, 2012a).

Documented evidence required to establish eligibility of C sequestration projects generally include restrictions on land uses where the project resides, a regime of maintenance for ongoing compliance, and a risk management strategy (Independent Pricing and Regulatory Tribunal, 2008). Aerial photographs or satellite imagery with on-site data are required as a bare minimum to enable landowners to register land use and land management changes. Accredited forestry sequestration activities and verification are often allowed to be undertaken roughly every five years, with a corresponding credit for each period. C assessments are calculated using models consistent with a corresponding standard, and sometimes include an appropriate uncertainty analysis. Uncertainty analyses are often used to reduce the final amount to ensure a conservative estimate (The New South Wales Government, 2005). Vegetation that involves rotational harvesting at some point requires a more sophisticated C modelling and accounting system than simple conservation plantings. Eligible certificate creation for rotational harvesting usually requires C stocks never to fall below the threshold of certificates created (Independent Pricing and Regulatory Tribunal, 2008).

Environmental and Land-Use Change Policy Ambiguity

The final forest C offset rules that will apply in Australia's climate change mitigation policies are yet to be determined. The Commonwealth Government has indicated its intention to review the development of longer term arrangements (The New South Wales Government, 2008). The previously proposed CPRS White Paper stated that offsetting will be likely allowed from sectors outside C policies (Cosier et al., 2009), and this is likely to be the approach followed by successor policies. As the agricultural sector will likely be excluded from the C policy liabilities, landholders will be eligible to create C offsets for captured sectors. Landholders, certain leaseholders and C property rights holders can apply to become accredited forest entities, which will be published by any scheme regulator. To be eligible for the first Kyoto Protocol (KP) commitment period permit entitlements, forests were to be registered before 1 January 2013 (Cosier et al., 2009).

There is likely to be continued developments occurring in the creation on new forest and ecological management markets, of which have some precedence in the KP requirements for LULUCF inclusion into national inventories. The COP 13 in Copenhagen secured further interest in market mechanisms to improve forest management under the Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD Programme). Forest management is defined as "a system of practices for stewardship and use of forest land aimed at fulfilling relevant ecological (including biological diversity), economic and social functions of the forest in a sustainable manner" (United Nations Framework Convention on Climate Change, 2002) p 58. The KP's Article 3.4 includes the option of accounting for forest management, revegetation, cropland management, and grazing land management to be included in national targets. Of particular interest in Australia is ecological market developments relating to grazed woodlands and rangelands, which are accounted under the Grazing Lands component of Article 3.4 (Richards, 2001). As Australia currently chooses not to account for article 3.4 emissions, there is a possibility that some of these management activities will become involved in future markets under international frameworks. Thus, it is only logical to compile and develop monitoring and quantitative methods of proxy ecological indicators of such expanding management and conservation policies in addition to simply biomass and C NPP. It is interesting to contrast how far land use policies have come in Australia over a relatively short space of time. This may also be a source of concern to landholders seeking to undertake long-term commitments, as Australian policymakers, even in the same jurisdiction, have tended to provide little consistency over time (McHenry, 2012a).

Lessons Learned From History: Land-use Market Risks

The WA Government's Conditional Purchase (CP) crown land release scheme was first introduced in early WA settlement, but was reinvigorated in 1961 and continued until 1982. Each property in the CP scheme was purchased for only around 35 cents per ha (in 2010 Australian dollars), which included the government provision of land surveys, road access, and telephone services. This attracted many unfamiliar with land management to implement the minimum conditions of the CP scheme, which were to clear two-thirds of the property and fence the boundary within a given period. This resulted in high rates of farm failure, and a resultant over-clearing from successful neighbours to recover costs of overextending themselves by acquiring the failed properties. Despite the known soil, biodiversity, productivity losses and associated salinity issues at the time, the amount of clearing facilitated by the WA Government between 1980 and 1990 in four significant bioregions totalled between 80,000 and 160,000 ha each year (Australian Greenhouse Office,

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2000). (Table 5) The combined impact of government land development schemes, tax incentives and easy finance lead to a scarcity of uncleared arable land. Thus, native vegetation clearing policies were replaced by staunch clearing control legislation. The WA Government policy now favours conservation and a greater landholder involvement (Australian Greenhouse Office, 2000; Van Vreeswyk et al., 2004).

Table 5. Clearing in four significant Biogeographic regions (IBRA) between 1980 and 1990. Source: (Australian Greenhouse Office, 2000).

IBRA region	Estimated clearing (ha yr^{-1})
Wheatbelt	10,000 – 20,000
South-eastern	50,000 – 100,000
Coastal	10,000 – 20,000
South-western	10,000 – 20,000
Total	80,000 – 160,000

Environmental Market Development Guidance from Carbon Market Land-Use Experience

An indication of the order of value of future environmental markets can be approximated by expected values for C sequestration. The Cooperative Research Centre for Greenhouse Accounting (CRCGA) undertook a case study of the profitability of 'C farming' in Western Australia. The CRCGA used a 60 year discounted cashflow analysis that included the commercial wood products produced, the additional potential value of C, and the administration and other costs associated with C forestry. The study combined the local government regional data for average productivity per ha with a forestry project analysis to obtain an 'operating return per effective ha' for landholders engaging in a C sequestration activities. The results for the high rainfall areas (900 mm of annual rainfall) were encouraging with Australian dollars (AUD) 10 per tonne C credits supplementing the net present value (NPV) timber income by 16% for a *Eucalyptus globulus* (blue gum) plantation, 62% for a *Eucalyptus saligna* (Sydney blue gum) plantation, and AUD560 ha^{-1} for unidentified native forest species revegetation (The CRC for Greenhouse Accounting & Tony Beck Consulting Services Pty Ltd, 2003). However, the range of monitoring, verification and certification cost estimates for C farming from some selected studies show the great variability in potential expenditures. Specht and West (2003) included information on the likely costs associated with a sampling program of the type required for C trading using professional measurements teams. To achieve the required level of sequestration confidence on the 350 ha of estates would require assessment of around 150 tree plots and 80 soil sites. This would cost around AUD5,000 or AUD240 ha^{-1}, which included the team's accommodation costs (Specht & West, 2003). However, the CRCGA chose in their modelling that an appropriate cost would be in the range of AUD12.50 ha^{-1} per analysis. Whatever C accounting costs become, they will need to be assessed every five years, or at the start and end of each commitment period (Booth et al., 2003; The CRC for Greenhouse Accounting & Tony Beck Consulting Services Pty Ltd., 2003). The CRCGA study stated that while the C price is AUD5 to AUD10 tCO_2-e, it is not profitable to establish C sinks in their own right anywhere in WA. At AUD15 tCO_2-e the CRCGA found it would be profitable to establish trees for conventional timber products and C, even across the highly productive agricultural lands in Great Southern and into the Southwest regions, only when the cost of land is not taken into account. The study concluded that C farming/forestry activities could not compete commercially with current landholder activities, but may be complementary to such activities or offset potential losses from establishment costs of windbreaks and revegetation (The CRC for Greenhouse Accounting & Tony Beck Consulting Services Pty Ltd., 2003). Effectively achieving this complementarily will require low C accounting costs, an intimate knowledge of the land, and its productive potential (McHenry, 2013).

Biological Complexity and Environmental Markets Using a Forestry Example

At the landscape scale, soil types, soil texture, local topography, water availability and the condition and exposure of individual trees influence many aspects of vegetative NPP (Kort & Turnok, 1999). Open-spaced trees are subjected to greater mechanical wind stress and respond by increasing the thickness of stems, branches, and particularly the root system (Ritzon & Sochacki, 2002). The proportion of total tree biomass in roots is generally between 30 - 50% of aboveground biomass (Kort & Turnok, 1999). However, it is known that planting trees in higher densities, such as in a windbreak or plantations, reduce the percentage of tree biomass in root systems. The amount of aboveground biomass also increases as the trees age relative to the biomass in roots. This is more pronounced with open spaced trees than close-spaced trees (Ritzon & Sochacki, 2002). For reasons of practicality, estimating the biomass of smaller shrubby plants is best related to shelterbelt volume; as the space occupied by the total leaf area available for photosynthesis is independent of the number of trees in the windbreak because the lateral growth is limited by their neighbours (Kort & Turnok, 1999).

Additional intricacies discovered by site analyses are the variability of soil organic C (SOC) below plantations and adjacent land. Short-term declines in SOC following LUC from pasture to plantation in wetter regions requires landholders and modellers to account for these losses in particular bioregions. The SOC levels would be expected to recover and possibly exceed the pre-plantation level (Kirschbaum, 2000; Specht & West, 2003). Such assumptions require on-site verification to refine models that aggregate data for market mechanisms and formal accounts, such as Australia's National Greenhouse Gas Inventory (NGGI) (Brack & Richards, 2002; Booth et al., 2003).

There are significant biological complexities in establishing large vegetative stocks for new markets which are poorly understood by markets and current biometric models. Although external to any C market transaction, negative environmental consequences may occur in relation to water availability in sensitive catchments due to large reforestation activities consuming sizeable quantities of water (Department of Climate Change, 2008; Cosier et al., 2009; McHenry, 2012b). This will require estimation, planning and management by local and state governments if such activities are projected to become widespread within their planning horizons. The development of transparent mechanisms to quantify the performance of activities will be crucial.

All biological conservation-based projects are subject to additional market risk, but are also impacted by physical risks associated with fire, drought, or pests, which must be reasonably accounted for (The CRC for Greenhouse Accounting & Tony Beck Consulting Services Pty Ltd., 2003). Compounding these issues are the policy change concerns for landholders, including permanence issues arising from participation in conservation activities, most of which are likely to be around 100 years or even permanently on titles or leases (Booth et al., 2003; The CRC for Greenhouse Accounting & Tony Beck Consulting Services Pty Ltd., 2003; Independent Pricing and Regulatory Tribunal, 2008). The risks of limiting future management options is crucial for landholders, which may result in future compensation payments to carbon rights holders if contractual obligations are annulled by landholders (if this is possible) in addition to associated transaction costs (Booth et al., 2003; The CRC for Greenhouse Accounting & Tony Beck Consulting Services Pty Ltd., 2003).

Conclusion

The integration of high accuracy on-site vegetative and ecological data into landscape and macro-scale land monitoring models will enable new market mechanisms that internalise environmental externalities from land management activities by providing both accurate and precise on-site accounting and verification. This approach has the potential to achieve several efficiencies including new skilled conservation jobs in remote areas, reduced capital and infrastructure duplication for on-site environmental monitoring, streamlined government administration and research ancillary expenses, locally appropriate conservation activities that are sustained over time, and direct communication between landholders, academic institutions, and land management policymakers.

Striking an operative balance between the accuracy of market product value, the genuine value of on-ground activities, and the associated market administrative and monitoring costs will necessitate on-site activities on both private and government lands. Policymakers should be aware that landholders, due to their relationship with the land, generally hold the majority of high resolution data regarding the efficacy and nuances of particular land use and management alternatives (Stoneham, 2009). Experience has shown that land management activities undertaken by governments or external entities in regional areas often under-perform, and initiatives are rarely funded sufficiently to be sustained effectively (Van Vreeswyk et al., 2004; Stoneham, 2009). The option of subcontracting landholders who live and work in such regions may be a more effective solution to increasing travel and accommodation costs of centralised contractors. An open relationship between policymakers and landholders will therefore assist the development of appropriate management practices that provide private landholder security, public good protection and enhancement, alongside efficiency in terms of administering limited environmental funding. This will more effectively harness the considerable existing knowledge and capacity in rural, regional, and remote Australia and assist the generation of detailed knowledge of ecosystem functional change.

Pressures from industry expansion, urban encroachments, and conservation objectives on existing regional food production systems and culturally sensitive lands will likely intensify over-time. Improving the interface between landholders and policymakers through rigorous monitoring mechanisms provides a much needed additional communication channel between landholders and those not on the land, but with an external interest in it. With sufficient knowledge and resources, private on-site landholders are often best placed to quantify the productive potential of their land, and develop appropriate and cost-effective management activities. An internalisation of non-monetary land systems can generate a more effective and sustained land management and environmental outcome that do not require acquisition or expensive maintenance regimes by governments. Therefore, it will be prudent for policymakers and researchers to work more transparently with private long-term landholders to maximise benefits and minimise costs from new market opportunities, maintain ecological services, and retain food productive capacity.

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