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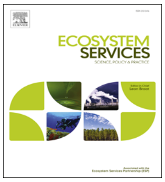

Measurement matters in managing landscape carbon

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ABSTRACT

Carbon stocks and emissions are quantified using many different measures and metrics, and these differ in their surrogacy, measurement, and incentive value. To evaluate potential policy impacts of using different carbon measures, we modeled and mapped carbon in above-ground and below-ground stocks, as well as fluxes related to sequestration, oxidation and combustion in the Ex Mega Rice Project Area in Central Kalimantan, Indonesia. We identify significant financial and carbon emission mitigation consequences of proxy choice in relation to the achievement of national emissions reduction targets. We find that measures of above-ground biomass carbon stock have both high measurement and incentive value, but low surrogacy for potential emissions or the potential for emissions reductions. The inclusion of below-ground carbon increased stocks and flows by an order of magnitude, highlighting the importance of protecting and managing soil carbon and peat. Carbon loss and potential emissions reduction is highest in the areas of deep peat, which supports the use of deep peat as a legislative metric. Divergence in patterns across sub-regions and through time further emphasizes the importance of proxy choice and highlights the need to carefully consider the objectives of the application to which the measure of carbon will be applied.

1. Introduction

Land use and land cover change is responsible for a third of global anthropogenic greenhouse gas emissions over the last 150 years (Houghton et al., 2012), and ongoing deforestation and forest degradation is the major source of current greenhouse gas emissions in many tropical developing countries (Van Der Werf et al., 2009). Climate change mitigation and adaptation is now a strategic part of many national economies and environmental policies (Capoor and Ambrosi, 2008). This includes a strong emphasis on activities under the program for Reducing Emissions from avoided Deforestation and forest Degradation (REDD+) and other similar voluntary mechanisms aimed to reduce greenhouse gas emissions in developing countries.

Information on carbon stocks and projections of future emissions over space and time is required at multiple stages of the development and implementation of climate change policy including carbon accounting (Lim et al., 1999) and land use planning (Achard et al., 2004). Specifically, it is needed to establish baselines (Lubowski et al., 2006), prioritize the location of emissions reduction or sequestration activities (Naidoo et al., 2008), and for the monitoring, reporting and verification (MRV) of such activities (Petrokofsky et al., 2012).

The main pools of carbon in forested ecosystems are the stores of above- and below-ground living biomass, necromass (litter, and woody debris), and soil organic matter. Deforestation and degradation visibly impacts above-ground stores, however soils and particularly peat soils are also a significant source of emissions following deforestation and forest conversion (Houghton et al., 2012; Page et al., 2002). There are a multitude of methods for assessing above- and below-ground carbon stocks, and these have been extensively reviewed (Gibbs et al., 2007; IPCC, 2006; Ladd et al., 2013; Petrokofsky et al., 2012; Qureshi et al., 2012; Vieilledent et al., 2012; Ziegler et al., 2012). All reviews conclude that comprehensive, field-derived carbon measures are labor intensive, time consuming, expensive, often destructive (Gibbs et al., 2007), and therefore generally prohibitive over extensive areas.

As a consequence, indirect methods of measuring carbon stocks and emissions, referred to herein as *proxies*, are common. Here we

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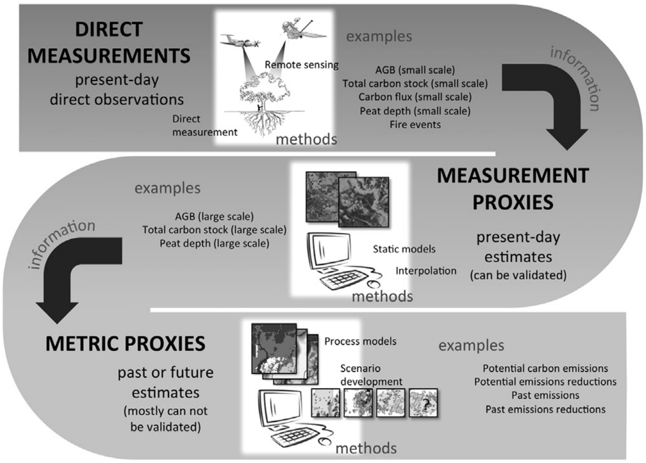

Fig. 1. Differences between measurements, measurement proxies, and metric proxies.

distinguish between two groups of proxies: those developed at a measurement-level and those developed at the level of metrics (Fig. 1). *Measurement-level* proxies are those that can substitute for direct measurements, whereas *metric-level* proxies are typically a combination of numerous measurement-level proxies and are often derived through process-based modeling. Both types can be extrapolated or indirectly estimated over extensive areas.

Measurement-level proxies include carbon stocks and fluxes of above- and below-ground carbon at a particular point in time. These proxies are substitutes for direct field measurements: they usually involve information collated from a number of field measurements that are extrapolated using additional landscape variables such as vegetation type (Couwenberg et al., 2011; Saatchi et al., 2007), elevation (Saatchi et al., 2007), rainfall (Saatchi et al., 2007), soil type (Kapos et al., 2008), and peat characteristics such as water level and subsidence (Fig. 1; Joosten and Couwenberg, 2009). Importantly, as these measurement-level proxies are of current processes, they can be verified at the time of estimation.

Metric-level proxies are typically derived from process models that combine many of the above mentioned measurement proxies and biophysical parameters, as well as assumptions regarding changes in these over time. Proxies at the level of metrics include both measures of potential emissions and the potential for emissions reduction (Fig. 1). These proxies can be used to predict biomass production and carbon dynamics over space and time (e.g. CENTURY; Parton et al., 1995) and the impacts of reforestation (e.g. 3-PG; Bryan and Crossman, 2013; Paterson and Bryan, 2012) and agricultural development (e.g. APSIM; Luo et al., 2013; Zhao et al., 2013). Typically calibrated against field data, a major strength of the process models used to develop metric-level proxies is their ability to forecast carbon sequestration and emissions under different scenarios of change (Crossman et al., 2011; Liu et al., 2009). Activities such as land-use planning necessarily deal with potential future emissions necessitating these forecast estimations (Couwenberg et al., 2010). The use of counterfactual baselines in such forecasts essentially mean that potential emissions reductions can never be verified (i.e. directly measured), and although potential emissions may be verified this necessarily must be *post hoc*, after decisions are made based on the available proxy information.

The performance of different carbon proxies has been the focus of past studies, particularly how well the proxy correlates with the true measurement, both spatially and temporally (i.e. its surrogacy value), and how easy or expensive it is to derive (i.e. its measurement value). For example, remotely sensed above-ground biomass (AGB) has been extensively compared to field-based measurements (Petrokofsky et al., 2012) and vegetation-based proxies for carbon flux have been compared with direct carbon flux measurements (Couwenberg et al., 2011). There has also been extensive comparison among metric-level proxies (Houghton et al., 2012). However, there has been little comparison between measurement and metric-level proxies and it is often assumed explicitly or implicitly that carbon stocks are an adequate proxy for the potential for emissions reduction (Chan et al., 2011, 2006; Egoh et al., 2010; Larsen and Harvey, 2010; Reyers et al., 2012; Wendland et al., 2010). When considering carbon proxies in a policy or planning context, it is also important to recognize that each proxy will differ in how easily the proxy is communicated and the extent to which it translates to actions and the other co-benefits it might encompass (i.e. its incentive value). This 'framing' of proxies can thus influence the overall performance of policies, even when the measurement or surrogacy values remain the same (Entman, 1993; Druckman, 2001).

The required performance of a proxy across these three dimensions (surrogacy, measurement, and incentive value) is dependent on the specific activity of interest. Land use planning undertaken by governments may place more importance on measurement and surrogacy value, whereas activities that rely on community involvement and acceptance may give greater importance to the incentive value of a proxy. The choice of proxy and how they are applied are likely to influence the perceived priority, cost-effectiveness, and impact of specific climate change mitigation or abatement activities in specific locations (Paterson and Bryan, 2012). Poor choices in this regard may result in inefficient and ineffective mitigation outcomes.

Here we explore the consequences of using different carbon proxies by modeling, mapping, and evaluating the surrogacy, measurement and incentive value of seven proxies of landscape carbon (Table 1) for the Ex Mega Rice Project region in Central Kalimantan, Indonesia (Fig. 2). This case study region is of considerable global interest due to continuing high carbon emissions resulting from past land use change. We determine the financial and carbon emission mitigation consequences of proxy choice in relation to the achievement of Indonesia's national emissions reduction targets, and discuss the performance of the different proxies, particularly in the context of their utility for informing and evaluating land use plans.

2. Materials and methods

2.1. Study region

The Ex Mega Rice Project (EMRP) region (Fig. 2) defines an area subject to an agricultural self-sufficiency and development policy implemented from 1996 to 1998 that cleared one million hectares of tropical lowland peat swamp forest and created 4000 km of canals for drainage and irrigation in Central Kalimantan, Indonesia (Page et al., 2009). The project failed to achieve its agricultural objectives, with subsequent agricultural land abandonment and ongoing degradation resulting in considerable negative consequences for hydrology and carbon emissions. After the peat lands were drained, a process of drying, oxidation, and irreversible collapse occurred (Wosten et al., 2008), increasing peat susceptibility to fire (Hooijer et al., 2006) and releasing significant amounts of greenhouse gases to the atmosphere (Page et al., 2002), particularly in extreme El Niño years (Ballhorn et al., 2009; Hooijer et al., 2010; Page et al., 2002). Widespread peat fires in the 1997 El Niño event attracted considerable international attention due to regional human health effects (Aditama, 2000) and the volume of carbon released into the atmosphere (Page et al., 2002). The land use changes across areas such as the EMRP

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