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Uncertainty in establishing forest reference levels and predicting future forest-based carbon stocks for REDD+

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ABSTRACT
Forest reference levels (FRLs) provide a benchmark for assessing reduced emissions from deforestation and forest degradation (REDD+), and they are central to demonstrate additionality of REDD+. Attaining realistic FRLs, however, is challenging, especially in complex mosaic landscapes. We established FRLs in northern Laos for different reference periods and tested them against actual carbon stock changes. Annual time series of Landsat satellite images were used to capture the subtle changes in carbon stocks in complex landscapes characterized by shifting cultivation. We found that FRLs differ considerably depending on the reference period chosen. Abrupt land-use changes occurred when hybrid maize replaced traditional shifting cultivation and forests, and this invalidated carbon stock trends that would have been predicted had the FRL been projected into the future. We conclude that demonstrating additionality of REDD+ in fast developing areas is difficult and that payment systems rewarding potential emission reductions against hypothetical extrapolation of FRLs are unlikely to be a cost-effective strategy.

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Carbon emissions; Climate change; Deforestation; Forest reference levels; Land use change; REDD+

1. Introduction

Negotiations on a mechanism for Reducing Emissions for Deforestation and Forest Degradation in Developing Countries (REDD+) under the United Nations Framework Convention on Climate Change (UNFCCC) have reached a stage where implementation is now possible. However, many scientific challenges and disagreements still make REDD+ implementation look very complex and uncertain (Allan & Dauvergne, 2013; Mertz et al., 2012; Visseren-Hamakers, Gupta, Herold, Peña-Claros, & Vijge, 2012) despite new evidence that direct payments at the local level may indeed reduce deforestation (Jayachandran et al., 2017). One of the important debates in REDD+ is how to establish forest reference emission levels (FREL) or forest reference levels (FRL) – the benchmarks used to calculate carbon credits that should be paid to participating countries for future emission reductions or enhancement of carbon stocks. Whether and how much a participating country

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receives in REDD+ funds will depend on the FREL or FRL. A credible and accurate reference level is therefore critical to ensure additionality of funding for REDD+ (Herold, Angelsen, Verchot, Wijaya, & Ainembabazi, 2012; Müller et al., 2014; Sloan & Pelletier, 2012).

FREL and FRL are used seemly interchangeably in the discussion of reference levels of REDD+. While the UNFCCC never explicitly defined the differences between FREL and FRL, UN-REDD provides an explanation: 'A FREL includes only emissions from deforestation and degradation, whereas a FRL includes both emissions by sources and removals by sinks, thus it includes also enhancement of forest carbon stocks (http://www.unredd.net/knowledge/redd-plus-technical-issues/nfms-rel.html, checked 17 November 2017). For the purpose of this paper we will use the more comprehensive term FRL. Essentially, a reference level is the expected net carbon stock change (expressed in metric tons of carbon dioxide equivalent per year) in a baseline scenario without intervention. Various approaches have been developed to establish reference levels and include simple averages of historical net emissions, as Brazil proposed, and linear extrapolations of historical emission levels that to some extent may account for expected changes to drivers of deforestation or forest degradation that may not be reflected by historical averages (Huettner, Leemans, Kok, & Ebeling, 2009). UNFCCC suggests the development of reference levels should consider national circumstances to account for a country's development stage on the forest transition curve – a theory proposing the transition from high forest cover and low deforestation over periods of high deforestation to subsequent reforestation in the course of economic development (Mertz et al., 2012; Rudel, Schneider, & Uriarte, 2010). Since the capacity and context of countries implementing REDD+ vary, a stepwise approach can be applied to periodically update reference levels to incorporate new or better data as it becomes available (Herold et al., 2012). This concept was further developed by Köthke, Schröppel, and Elsasser (2014) who proposed to use standardized considerations of national circumstances that account for a country's development stage and then develop reference levels by positioning individual countries on the forest transition curve.

Twenty-five countries had submitted their forest reference emission levels to the UNFCCC by November 2017 (https://unfccc.int/land_use_and_climate_change/redd/items/8414.php, checked 17 November 2017). Most of the submissions use historical averages of land cover changes derived from remote sensing but some countries have used adjusted historical averages for various reasons. E.g. Guyana argues for low deforestation in the past but expects increasing deforestation than the reference period would indicate. Colombia also expects higher future deforestation due to reduced armed conflict and thus adjusts future projected emissions upwards by 10%. However, many of these submissions still face several challenges. They do not account for changes in known or the emergence of new future drivers that may set off rapid and unpredictable shifts in land use and deforestation rates, as often occurred in the past (Müller et al., 2014; Ramankutty & Coomes, 2016; Sun & Müller, 2014), and they are also sensitive to the definition of forest cover, which is up to the individual countries to determine (Romijn et al., 2013). Moreover, Sloan and Pelletier (2012) modelled spatial projection of forest reference levels (in their paper termed baselines) for Panama for the 2000–2008 period against actual forest change and showed that these reference levels had limited value for REDD+ due to accuracy related to, amongst others, complexities of forest cover change and spatial variability in forest carbon density. Nonetheless, most countries are using these simple projection techniques and there is an urgent need to assess the feasibility of the FRLs as a tool for calculating REDD+ credits and for ensuring that the credits reduce emissions beyond the level that would have happened in their absence – the principle of additionality.

Most FRLs are made at national level, but it can be an advantage to test how well such predictions of C-stock changes will work at sub-national levels where the local dynamics and drivers of change are better known. Ankersen et al. (2015) showed that if FRLs – or business as usual scenarios as the authors labelled them – had been established for a district in Nghe An Province in Vietnam in the 1970s, 1980s and around 2000, they would all have been a poor predictor of the actual trends in forest cover and its quality, which were strongly influenced by policies on reforestation and market developments stimulating agricultural intensification (Ankersen et al., 2015; Sikor, 2001). The change detection analysis by Ankersen et al. (2015) was based upon post-classification comparison of five Landsat images between 1973 and 2011, which is in line with some of the methods used recently in the official country submissions (e.g., Ecuador used two time steps). Recent developments in image availability, processing and time series analysis, however, have enabled the use of the full Landsat archive for time series based change studies (Broich et al., 2011; Huang et al., 2010; Kennedy, Yang, & Cohen, 2010). Dense Landsat time series (sub-annual to annual observations) can capture the subtle changes in spectral properties and identify abrupt change or slower, continuous degradation processes (DeVries et al., 2015; Hamunyela, Reiche, Verbesselt, & Herold, 2017). By accurately identifying the time since clearing, information on forest structure can be gained, which is a key parameter to understanding biomass density (Pflugmacher, Cohen, & Kennedy, 2012). Combining annual time series with biomass growth functions can therefore capture carbon stock dynamics in highly variable systems involving clearing and regrowth cycles, such as shifting cultivation (Inoue et al., 2010; Kiyono et al., 2007). Such a method has not been used in the national communications of countries listed above and it has only recently been experimented with in the Amazon (Dutrieux, Jakovac, Latifah, & Kooistra, 2016). If proven successful at the sub-national level, it could be a new way to address FRLs at national level.

In this paper, we have two main objectives: 1) to demonstrate how dense annual time series of land cover data from high resolution satellite imagery, combined with locally derived biomass allometrics, can provide spatially and temporally detailed analysis of historic land cover change and carbon stock changes; 2) to take a retrospective approach to testing the validity of the hypothesis that it is possible to use FRLs as a basis for calculating REDD+ credits. This is similar to what was done in Ankersen et al. (2015), but here we can provide a more comprehensive and robust analysis given the improved temporal depth of the satellite image analysis (annual time series). Specifically, we test what would have been the result if REDD+ projects had been planned in the past and based on FRLs developed at that point time. We compare this to the actual carbon stock changes that occurred after the hypothetical REDD+ decision and thereby show to what extent additionality would have been achieved – or whether a decision to not implement REDD+ would have led to deforestation despite FRLs indicating reforestation trends. Northern Laos is used as a case area for this historic assessment to generate provincial and district level FRLs as it effectively represents Southeast Asian (and other) landscapes where sudden, unforeseen, or dramatic shifts in land use practice are occurring (Müller et al., 2014; Schmidt-Vogt et al., 2009).

2. Study area

Laos is engaged in the REDD+ agenda and moving towards REDD+ readiness in policies and institutional structures (Lestrelin et al., 2013), albeit at a slow pace and with sometimes contradicting conservation and land development policies (Vongvisouk, Castella, et al., 2016). Huaphan Province (Figure 1) is ideally suited as a case study because of dynamic and rapidly changing land use and because several projects are engaged in REDD+ pilot implementation. The province is traditionally a shifting cultivation area that has been increasingly influenced by more intensive cash cropping systems and contract farming in recent years (Thongmanivong & Fujita, 2006; Vongvisouk, Broegaard, Mertz, & Thongmanivong, 2016; Vongvisouk, Mertz, Thongmanivong, Heinimann, & Phanvilay, 2014). Large tracts of land formerly used for upland rice under traditional shifting cultivation started being cleared and replaced by permanent or hybrid maize cultivation with short fallowing in the 2000s. By 2010, this development was already turning into a veritable 'maize boom' (Keophosay, Viau, Jobard, Lestrelin, & Castella, 2011; Vongvisouk et al., 2014), a development that would have been difficult to foresee before 2004 when practically no contract farming schemes were established in the area.

In 2003 the Wildlife Conservation Society (WCS) started managing the Nam Et – Phou Loey National Protected Area (NEPL-NPA), which covers a large part of the western districts in Huaphan Province, especially Hiem and Sone Districts (two new districts after Viengthong District was split in

Figure 1. Map of Huaphan Province indicating the Nam Et Phou Loey National Protected Area and the 10 districts. The province covers an area of 17,190 km^2.

2014), see Figure 1. WCS manages the NEPL-NPA with land demarcation, land use planning, law enforcement, and extension activities that could also be components of a REDD+ project. Indeed, the area is selected by the Lao REDD+ Task Force as a demonstration area for REDD+ and the intention was to implement a REDD+ project in NEPL-NPA area. The Climate Protection for Avoided Deforestation (CliPAD) project, supported by the German agency for international cooperation (GIZ), planned this area as one of their main target regions for a pilot-REDD+ project. However, the feasibility analysis showed that the REDD+ project would not be economically viable due to 'lack of deforestation' (Moore, Eickhoff, Ferrand, & Khiewvongphachan, 2011). Since 2013, two REDD+ projects (CLIPAD and LEAF – www.leafasia.org) are jointly piloting a jurisdictional approach to REDD+ at the provincial level, with field activities conducted in a few target districts and carbon accounting managed at the provincial level.

3. Methods

The analysis is conducted at two spatial levels: 1) the core of the study comprising the entire Huaphan Province and 2) a district level analysis with a specific focus on two districts with contrasting history of forest cover change: the former Viengthong District and Hua Meuang District (Figure 1). The analyses build on a historic assessment of carbon stock changes associated with deforestation and forest degradation between 2000 and 2012. Different reference periods after 2000 are used to predict 'future' carbon stocks. The predictions are generated by extrapolating the hypothetical baseline and are then compared with the real estimates of carbon stocks for the hypothetical monitoring period. Reference periods before 2000 cannot be established as the availability of the Landsat data is too limited for attaining annual time series of land cover changes, as employed in this paper.

3.1. *Land cover change detection using remote sensing data*

Mapping forest age directly using satellite data is difficult, but forest age may be indirectly estimated from the time of clearing or burning, assuming that natural vegetation starts to regrow a year after clearing and cultivation. The concept has been applied in temperate forests (Cohen, Harmon, Wallin, & Fiorella, 1996) and tropical forests (Helmer et al., 2010; Inoue et al., 2010). To develop fallow age maps and the time of clearing, we used annual disturbance maps at a spatial resolution of 30 meters derived from dense time series of Landsat TM and ETM data (Pflugmacher et al., 2013). When analysed in sequence, the imagery provides estimates of time since clearing for each Landsat pixel allowing us to reconstruct the per-pixel age distribution of fallow vegetation. The Landsat time series was highly fragmented from 1988–1999, with 4 years missing data, and other years having only partial coverage. From 2000 onwards however there was full areal coverage for every year. We therefore chose to focus our analysis on 2000–2012 period where reliable change estimates could be made.

The initial land cover for 2000 included three land cover types derived from the classification of Landsat imagery: dense forest, open forest (fallows), and non-forest (including settlements, croplands, and grasslands). Landsat time series available in the pre-2000 era were used to estimate fallow age for the base year 2000. For fallow areas, where no historical imagery was available, we assigned an average age of 10 years based on assumed pre-2000 average fallow lengths in northern Laos. There are very few studies that document fallow in Huaphan from this period, but one study based on data from 2000 showed 7–8 year fallow periods (Seidenberg, Mertz, & Kias, 2003). Studies from neighbouring provinces show a relatively wide range of average fallow lengths in the 1990s, from just 5–6 years in Luang Prabang (Roder, Phengchanh, & Maniphone, 1997) to 10–12 years in Oudomxay (Chen et al., 2001). Our assumption is that the relatively remote and less developed Huaphan Province probably was more comparable to Oudomxay than Luang Prabang at that time.

3.2. *Modelling historical carbon stocks*

Historical carbon stocks were modelled by combining annual land cover activity data with carbon density estimates for each land cover category. Estimates of carbon densities for different land covers vary in accuracy and the IPCC describes these levels as different 'Tiers' ranging from Tier 1 (lowest level of confidence) to Tier 3 (highest level of confidence). Tier 1 level assessments use IPCC default values for carbon pools in different forest biomes; Tier 2 uses country-specific data; while Tier 3 requires disaggregated and detailed inventory data of carbon stocks and relative change at subnational level.

IPCC Tier 1 estimates are the most widely used values for national carbon inventories and considered best practice when limited pre-existing data are available. While these estimates provide a good starting point and are generally applicable, the use of such generalized data omits local to regional variation in carbon density, introducing additional uncertainty into the emission estimates. To reduce this source of potential bias, we opted for carbon estimates by Kiyono et al. (2007), who used an empirical age-based carbon model. Their estimates are considered the most suitable data source available for our model as they: 1) are based upon data from the neighbouring province (Luang Prabang), 2) explicitly focus on the same forest/fallow agricultural systems found in Huaphan province, and 3) provide an annual increment of carbon density relative to forest age. The regionally specific attributes of this dataset allows a Tier 2 level estimate of carbon stock changes as employed in this paper.

The model by Kiyono et al. (2007) predicts carbon stored in fallow vegetation including four carbon pools; living biomass, dead biomass, litter and roots. Model predictions are based upon non-linear regression of plot measurements from forest fallow at different successional stages, ranging from 0.5 years (recently cleared fields) to 20.5 years (mature forest fallow). The sum of the four carbon pools was used to model total carbon density as a function of fallow age resulting in the following equation:

$$CD_a = 15.378\ In\ (Y_a) + 11.815$$

where CD_a is carbon density at age a, and Y_a is years since clearing at age a. We assumed this equation represented the chronosequential change of carbon density in forest fallows for Huaphan Province. For dense forests, we assumed an initial carbon stock of 81 Mg ha^{-1} based on estimates for tropical mountain forests (IPCC, 2006). Figure 2 shows an example of the carbon density maps that were developed for each year at provincial and district levels in order to develop the detailed FRL.

Inoue et al. (2010) used a similar approach, but they also used an empirical model to predict soil carbon as a function of fallow age. Here, we have not included soil carbon stocks. As a result, our carbon estimates are likely lower than the actual ecosystem carbon storage. However, we expect that the effects on the annual changes are negligible as results of field measurements indicate that differences in soil carbon associated with fallow length were not significant in the study region (I-REDD+, 2013; Roder, Phengchanh, & Keoboulapha, 1995). Thus, excluding soil may be justified for this study. We also acknowledge that belowground biomass may be considerably underestimated by current allometric equations used for secondary forests following shifting cultivation (McNicoll et al., 2015), but this would not substantially change the point related to inadequacy of FRLs made in the present article.

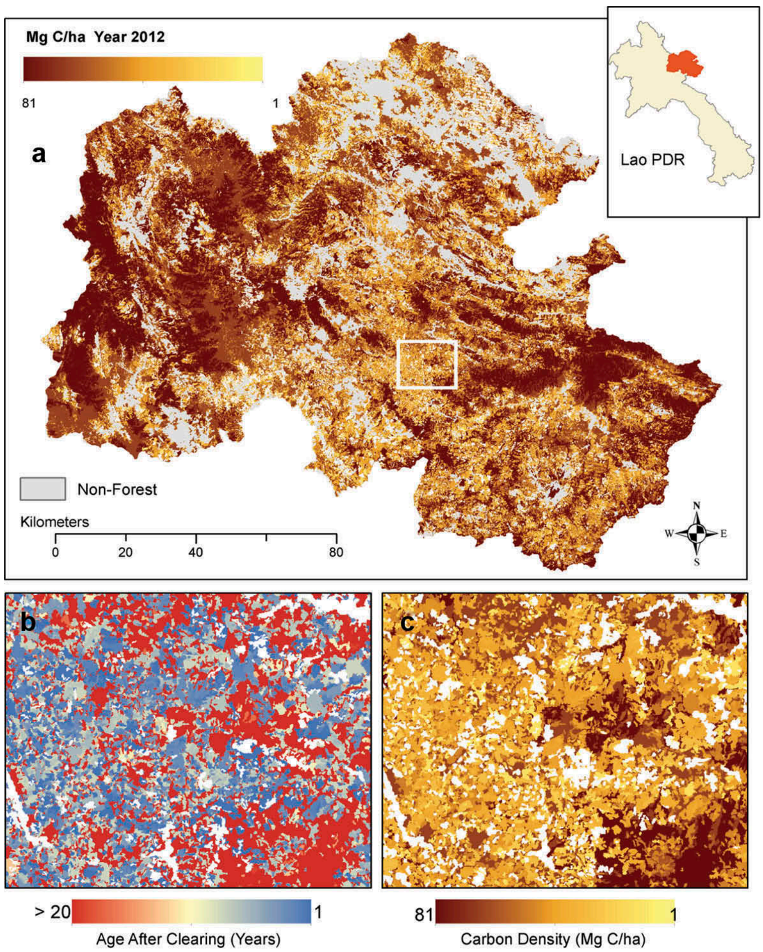

Figure 2. An example of carbon density maps produced for Huaphan province from 2012 (panel A). Such maps were created for each year from 2000–2012 to derive total carbon stocks shown in Figure 3. The year of forest/fallow clearing and recovery was estimated using dense Landsat time series resulting in an estimate of fallow age (panel B). A model that relates fallow age to carbon density was then used to estimate carbon density and carbon accumulation through time for each forest patch (panel C). Subsets of these data were also used to estimate carbon stock for Hua Meuang and Viengthong districts (Figures 4 and 5).

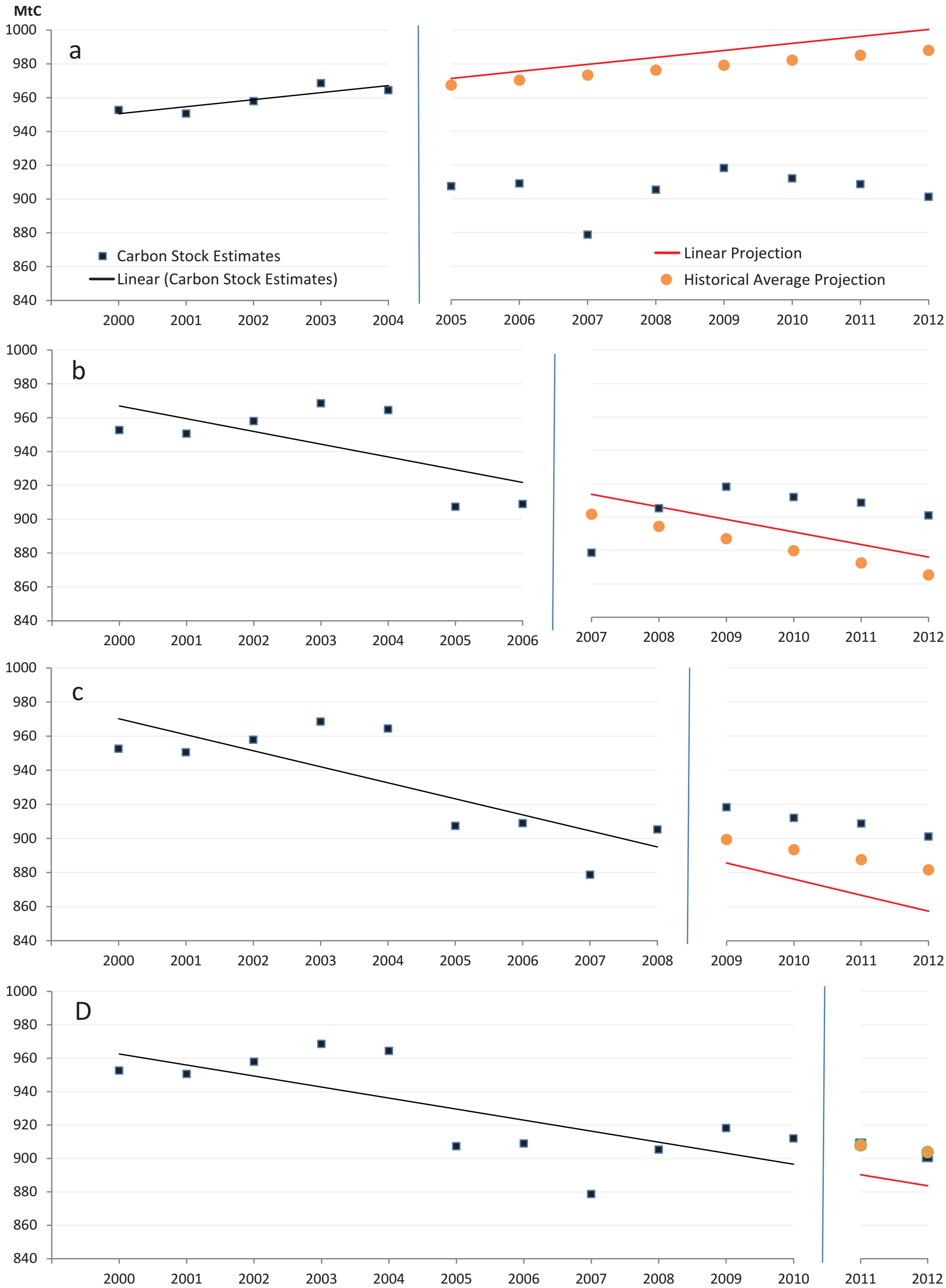

Figure 3. FRLs for Huaphan Province using four reference time periods, 2000–2004 (a), 2000–2006 (b), 2000–2008 (c), and 2000–2010 (d). The FRL is extrapolated into each hypothetical monitoring period using two methods: linear regression (red line) and historical average (orange circles). Actual estimated carbon stocks (MtC) are presented from 2000–2012 (dark squares).

4. Results

4.1. *Provincial level*

In order to assess the feasibility of initiating REDD+ activities at different points in time in the past, the historical carbon stock assessment were used to develop historical FRLs, measured in megatons

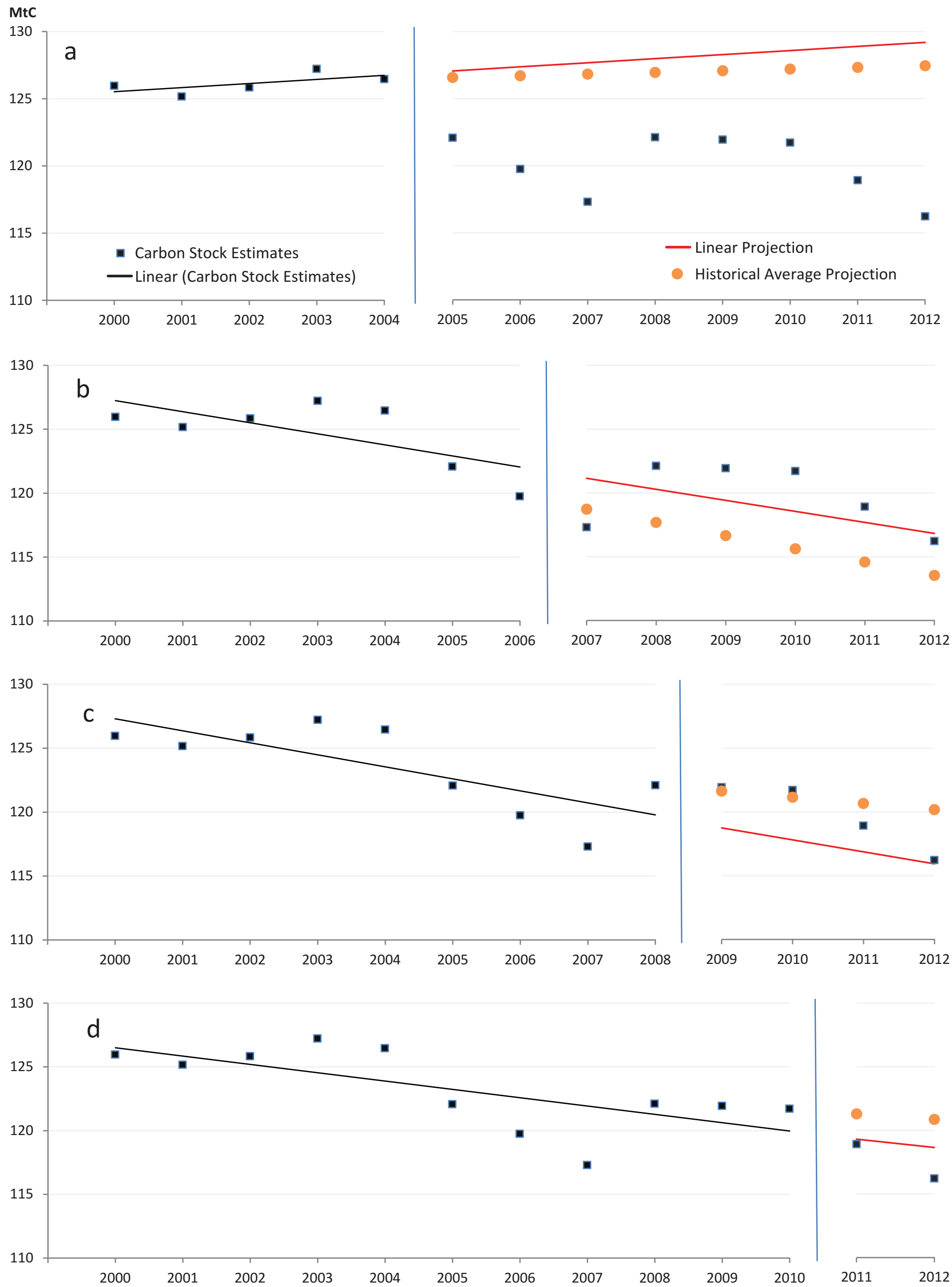

Figure 4. FRLs for Hua Meuang District using four reference time periods, 2000–2004 (a), 2000–2006 (b), 2000–2008 (c), and 2000–2010 (d). The FRL is extrapolated into each hypothetical monitoring period using two methods: linear regression (red line) and historical average (orange circles). Actual estimated carbon stocks (MtC) are presented from 2000–2012 (dark squares).

(Mt) carbon (C) per hectare, for different time periods in Huaphan province (Figure 3). The dark squares in each graph represent the total annual carbon stock for the province including both forest and fallow land cover strata from 2000–2012. Through this period the carbon stock was reduced from 953 Mt C in 2000 to 901 Mt C in 2012 causing an overall negative trend. This trend, however, is not in the form of a steady decrease in carbon stocks, but rather shows an alternating

Figure 5. FRLs for Viengthong District using four reference time periods, 2000–2004 (a), 2000–2006 (b), 2000–2008 (c), and 2000–2010 (d). The FRL is extrapolated into each hypothetical monitoring period using two methods: linear regression (red line) and historical average (orange circles). Actual estimated carbon stocks (MtC) are presented from 2000–2012 (dark squares).

pattern of both carbon emissions and sequestration as revealed by the annual time series. The estimated emissions in this period show an inter-annual range of 57 Mt C emissions in 2004 to 30 Mt C gains in 2007, with a mean and standard deviation of 4.3 (emissions) and 21.6 Mt C (gains) per hectare.

Each panel in Figure 3 represents an individual FRL based on progressively longer reference periods, 2000–2004 (A), 2000–2006 (B), 2000–2008 (C), and 2000–2010 (D). Two methods of predicting the historical carbon stock changes into each hypothetical monitoring period are presented: 1) linear extrapolation (red line): the future carbon stock is extrapolated based upon a linear regression, and 2) historical average (orange circles): the future carbon stock changes at the average annual rate of the reference period. A wide range of outcomes can be seen when the actual carbon stock estimates are compared to the predicted scenarios, ranging from overestimation (A) to underestimation (B, C, and D) of future carbon stocks.

The FRL in panel (A) of Figure 3 is based upon the shortest and most stable reference period from 2000–2004. In this scenario the predicted carbon stocks in 2005–2012 are significantly overestimated for all years. Using this FRL would in 2004 probably have led to the conclusion that REDD + activities would be unnecessary as it would be difficult to generate any credits with an FRL predicting increasing carbon stocks without REDD+. When comparing predicted vs. estimated carbon stocks, both prediction methods fail to capture the sudden and sustained drop in stocks beginning in 2005. This case demonstrates that land use does not always follow stable historical trends, but can be subject to nonlinear change that is difficult to predict.

In Figure 3 panel (B) the reference period runs from 2000–2006 and therefore includes the sharp drop experienced in 2005. In this case, the predicted carbon stocks are much closer to actual stocks when compared to panel (A), but stocks are consistently underestimated after 2008. Using this scenario, initiating REDD+ activities could have been considered feasible in 2006, but the rewards for emission reductions would have been overestimated because some of these reductions would have happened anyway. In other words, the inflated emission scenario would have led to an oversupply of reduction credits and the awarded emission reduction would not be additional as a result of the REDD+ activity.

In panel (C) the reference period runs from 2000–2008. Here the predicted carbon stocks are even closer to reality compared to (B). However an inflated emission scenario still remains. In panel (D) the reference period runs for 10 years (2000–2010) and the prediction of carbon stocks for the years 2011 and 2012 is fairly close to observed stocks. In general the sequence of scenarios presented suggests that a longer reference period may lead to more accurate predictions, but if another sudden drop in carbon stock were to occur in 2013, scenario (D) with the longest reference period, would fail to capture this. Predictions made by scenarios (B) and (C) would possibly be more accurate in this case.

4.2. *District level*

The carbon stock assessment at the district level showed that most districts in Huaphan followed a similar general pattern to that shown at the provincial scale, i.e. stable carbon stocks from 2000–2004, followed by a drop from 2005–2008, and a stable or fluctuating period between 2008 and 2012. Some districts showed more variation than others, and some experienced different magnitudes of carbon stock change compared to others. FRLs were developed for Hua Meuang (Figure 4) and former Viengthong district (Figure 5) as they represent two contrasting pathways with regard to carbon stocks within the province.

The historical pattern of carbon stock changes in Hua Meuang represents a typical pattern found throughout the province (Figure 4). The pattern displayed in Viengthong (Figure 5), on the other hand, represents an area that is atypical of the region as a whole, largely because of its relatively low population density and the large share of land under protection status in the NEPL-NPA.

Similar to the provincial scale, the FRL based on the short reference period (2000–2004) leads to overestimation of carbon stocks in both Hua Meuang and Vienthong (Panels A in Figures 4 and 5). In Viengthong, the historical average predictions vs. estimates have some similarities (2009–2011), however for other years there are large differences (e.g., in 2007 and 2012). In Hua Meuang the predicted stocks show no similarities to the estimated stocks.

Using the six-year reference period (Figures 4 and 5(b)) the predictions are improved depending on the approach. The linear regression predicts 2012 carbon stocks very well in Hua Meuang, while in Viengthong, 2012 stocks are accurately predicted by both the regression and historical average methods. Predictions from 2008–2011 tend to underestimate carbon stocks in both districts. Using longer reference periods as in panels (C) and (D) offers the same diversity in prediction accuracy depending on the reference period and approach used.

5. Discussion

The establishment of forest reference levels to predict future GHG emissions and thus ensure additionality of credits paid to compensate future emission reductions is one of the corner-stones of REDD+. The results of this paper clearly show that FRLs are highly dependent on the selected reference period and that abrupt changes in land use are virtually impossible to account for when reference levels are projected into the future. Thus, if REDD+ projects had been established in the past, the compensated avoided emissions would not have been additional to the counter-factual. We studied this in Huaphan Province, northern Laos because it is similar to the dynamic land use changes occurring in other parts of Laos and Southeast Asia that tend to be very erratic in nature and difficult to predict. This is partly because of a political-economic setting with conflicting land use policies, which on the one hand encourage better forest protection and governance and on the other hand promote development of market-driven cash crop production, both directly through government subsidies and indirectly by encouraging contract farming driven by the private sector (Broegaard, Vongvisouk, & Mertz, 2017; Dwyer, 2007; Vongvisouk et al., 2016; Willi, 2011). The communities in the two districts in focus here have indeed engaged in rapid adoption of cash crop production such as hybrid maize (Vongvisouk et al., 2016, 2014), while at the same time being engaged in various conservation efforts, e.g. low-emissions land use planning (Bourgoin, Castella, Hett, Lestrelin, & Heinimann, 2013), carbon stock measurements (Danielsen et al., 2013; Pratihast et al., 2014) and management of the Nam Et – Phou Loey National Protected Area (Moore et al., 2011). The reductions in forest cover observed in 2005 in the data presented in the present study are a clear indication of the maize expansion that took off in those years.

The results corroborate the few similar studies on this topic, e.g. the inability of 'business as usual scenarios' in Vietnam to predict future forest change (Ankersen et al., 2015) and the ability of a spatial model at national level in Panama to predict forest change in the absence of intervention (Sloan & Pelletier, 2012). The results also confirm more theoretical concerns on the feasibility of such approaches as land systems are difficult to predict due to frequently occurring nonlinear change (Müller et al., 2014; Ramankutty & Coomes, 2016) and thus provides much needed empirical evidence for these ideas.

Despite the difficulties associated with FRLs, policy makers in Laos and many other developing countries continue to emphasize FRL-based REDD+ as an important way to conserve forests and ensure financial transfers from developed to developing countries in order for the latter to both contribute to climate change mitigation and obtain additional funds for development. The Paris agreement at COP21 thus includes REDD+ as a key component (UNFCCC, 2015) and the national forest reference emission level (FREL) submissions to the UNFCCC rely on the formulation of future emission pathways, measured in tons of $C0_2$, as the basis for compensation. As we have demonstrated, this approach is problematic at the provincial level and certainly also at the national level (Sloan & Pelletier, 2012) and analysis of the ability of national submissions of FRELs to the UNFCCC to predict future emission scenarios in the absence of REDD+ are likely to show similar results.

As mentioned in the introduction, alternative approaches have been proposed to solve some of the complications of FRLs, such as the stepwise approach that would place lower demands on countries with lower capacity as proposed by Herold et al. (2012) and the forest transition curve related reference levels that also integrate standardized national circumstances of economic development as proposed by Köthke et al. (2014). However, none of these solve the intrinsic feature of uncertainty in reference levels and even though more advanced prediction models are developed, this may not increase the accuracy.

In addition to this overall debate on FRLs, our aim was also to examine to what extent more comprehensive and robust remote sensing based analyses in the common mosaic landscapes of Southeast Asia would be suitable for improving REDD+ planning at a lower scale than national level. Obviously, our analysis at the subnational level cannot solve the main concern of improving predictability in FRLs, but it does represent an important advance in the remote sensing based understanding of carbon stock dynamics of forest frontier landscapes dominated by shifting cultivation. Traditional classification and change detection methods based on bi- or multi-temporal methods from optical remote sensing cannot adequately capture the true dynamics of the system, primarily because fallow ages cannot be reliably distinguished (Hett, Castella, Heinimann, Messerli, & Pfund, 2012). Using such an approach means that generic carbon values are often attached to broad fallow categories, and therefore do not account for changes within the system (i.e. shortening or lengthening of fallow rotations), which can have significant consequences for the overall carbon balance. In the present study, we have therefore applied state-of-the-art methods using dense time series of Landsat images to ensure the reliability of change estimates with a temporal depth to adequately capture the overall age structure in a complex shifting cultivation landscape (Pflugmacher et al., 2013). This enabled us to capture the dynamic nature of the system on an annual basis as also proposed by others (Griffiths et al., 2014; Kennedy et al., 2010), and therefore provides a more realistic representation of historic carbon stock trends and thus a solid basis for calculating changes in CO_2 emissions.

Even if this may not be sufficient for calculating REDD+ credits it is highly useful for environmental planning to be able to understand trajectories of change and design development interventions in Laos and Southeast Asia, where shifting cultivation and poverty often converge (Heinimann et al., 2013). Moreover, scaling up the remote sensing methods proposed here to all forest areas at national level would require relatively moderate investment and this could be feasible even for countries that have limited resources and capacities for more manual work and for countries with substantial areas under shifting cultivation the proposed method will be highly efficient. In Laos, for example, a country-wide analysis could relatively easily be ground-truthed by the participatory land allocation exercises carried out in many parts of the country and by community-based monitoring that has been shown to be highly feasible in terms of accuracy and cost (Brofeldt et al., 2014; Danielsen et al., 2013) as well as to validate remotely sensed data (DeVries, Pratihast, Verbesselt, Kooistra, & Herold, 2016).

6. Conclusion

The main message from our analysis is simple and one which has not been developed in detail by previous research besides the study in Vietnam (Ankersen et al., 2015) that was limited in spatial extent and by few observations in time: Historical forest cover and emission levels can be improved with relatively simple methods involving dense time series of satellite images, but this does not solve the inherent problem of a flawed forest reference level concept that does not guarantee additionality of REDD+ payments. REDD+ may in fact be better off without predicting future emissions and calculating payments based on historical data in a situation where forest reference levels will produce different results depending on the period chosen and on how possible (unknown) future drivers are factored in. REDD+ payments may have to be simplified and linked to other indicators such as locality-specific best practices for climate change mitigation that could be compensated for directly and subsequently monitored. The experiment carried out by Jayachandran et al. (2017) in Uganda where a fixed amount in cash per hectare of forest was paid out to farmers to offset the opportunity costs of deforestation is a good example. Here the achieved cost of avoided emissions was low and the method avoided unnecessary and hypothetical estimates of counter-factual futures to estimate compensation.

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