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The critical importance of considering fire in REDD+ programs

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ABSTRACT

Fires are increasingly responsible for forest degradation in the humid tropics due to the expansion of fire-dependent agriculture, fragmentation, intensive logging practices and severe droughts. However, these forest fires have been largely overlooked by negotiations for Reducing Emissions from Deforestation and Degradation (REDD+). This paper examines how forest fires affect REDD+ schemes by compromising carbon permanence; undermining the potential of sustainable forest management and reforestation and regeneration activities in tropical countries; and threatening the additional benefits that can be accrued from REDD+, including biodiversity conservation and rural poverty alleviation. Narrowly focusing on avoiding deforestation, the sustainable management of forests or regeneration schemes will not always guarantee protection from fire occurrence, and investments in tropical forests may ultimately fail to achieve long-term emission reductions unless they also reduce the risk of forest fires. Integrating forest fire reduction into REDD+ presents many challenges, requiring: changes in agricultural practices that take place outside of the remaining forests; the monitoring and prediction of spatio-temporal patterns of forest fires across whole biomes; guarantees of additionality; avoiding leakage of fire-dependent agriculture; ensuring that responsibilities for fire management are fairly distributed; protection for rural livelihoods; and that any new activities result in positive outcomes for local people.

1. Introduction

Reducing Emissions from Deforestation and Degradation (REDD+) represents a set of policy approaches and positive incentives to reduce greenhouse gas emissions through the conservation and management of forests in developing countries. REDD+ includes five activities or interventions, namely: reducing emissions from deforestation, reducing emissions from forested degradation, sustainable management of forests, conservation of (existing) forest carbon stocks and enhancement of forest carbon stocks (e.g. through regeneration and planting in previously forest land). Under official safeguard guidance provided by the Cancun Agreements of the UNFCCC (Decision 1/CP.16) REDD+ activities should also be consistent, amongst other things, with "*the objective of environmental integrity and take into account the multiple functions of forests and other ecosystems*", as well as "*be implemented in the context of sustainable development and reducing poverty, while responding to climate change*".

Forest fires have important implications for all five REDD+ activities, as well as the intended additional environmental and social benefits. Although forest fires are historically rare in most humid tropical forests (Meggers, 1994), they have increased in extent and frequency since the 1960s due to the spread of fire-dependent agriculture such as cattle ranching (Uhl and Buschbacher, 1985), the increase in forest fragmentation and degradation (Siegert et al., 2001), and extreme climatic events leading to severe droughts (Cochrane et al., 1999; Lewis et al., 2011; Marengo et al., 2008). These fires include low-intensity understorey fires that can burn slowly through undisturbed or selectively logged primary forests (Barlow and Peres, 2004b), and higher intensity fires that occasionally reach into the canopy of forests that have been heavily logged, previously burned, or where weather conditions permit (Cochrane, 2003).

Despite the prevalence and importance of forest fires, to date they have received very little attention in REDD+ negotiations, capacity building and pilot work. For example, the UN-REDD

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Programme Strategy 2011–2015 does not refer to fire, and fire reduction has not been identified as an explicit REDD+ activity (Anon, 2011). Furthermore, very few national or individual REDD+ or Payment for Ecosystem Services (PESs) initiatives incorporate fire management, although the importance of fire reduction has recently been recognised in projects in Indonesia and Uganda (Anon, 2009; Peskett et al., 2011).

This paper examines the potential importance of fire for the REDD+ process. Recent negotiations at COP 17 in Durban emphasized the importance of environmental and social safeguards and associated information systems for the implementation of REDD+. Fire reduction represents both a valid forest conservation activity in its own right and a central environmental safeguard as it cuts across many of the issues relevant to the design, implementation and assessment processes of any REDD+ activity. First, we review the impact of forest fires on the permanence of carbon stocks in humid tropical forests, biodiversity conservation and human livelihoods. We then explore the challenges involved in incorporating fire-reduction strategies into REDD+ initiatives. Our focus is fire-sensitive humid tropical forests, which includes the closed-canopy evergreen forests that make up the vast majority of tropical forests in Asia, west Africa and Latin America: we do not consider fire-adapted ecosystems, including deciduous or semi-deciduous tropical dry-woodlands and savannas, which represent a very different ecological context and where fire reduction policies could have negative ecological consequences (Stickler et al., 2009).

2. The impact of forest fires on REDD+ priorities and safeguards

2.1. Tropical forest fires compromise carbon permanence

The increase in forest fires in the humid tropics (Cochrane, 2003; Cochrane and Barber, 2009) threatens the long-term permanence of carbon stocks in undisturbed primary forests, logged forests, and forest regeneration and reforestation projects. When measured against adjacent unburned forests, even low to medium severity fires in undisturbed or lightly degraded old-growth forest can kill over 50% of trees ⩾10 cm in diameter at breast height (Barlow and Peres, 2006a) (Fig. 1) and almost all of the larger woody lianas (Barlow et al., 2012; Cochrane and Schulze, 1999; Gerwing, 2002). Biomass loss depends on previous fire and land-use history (Fig. 1), and estimates of committed carbon emissions range from 40–62 Mg ha^{-1} (Balch et al., 2011) and 7.5–70 Mg ha^{-1} (Cochrane et al., 1999) equating to 15–140 years of carbon accumulation from above-ground biomass change in undisturbed Amazonian forests (based on estimates of 0.49 ± 0.19 Mg carbon ha^{-1} $year^{-1}$(Baker et al., 2004). Carbon emissions from tropical forest fires can exceed emissions from deforestation alone (~0.2 Pg C $year^{-1}$) in extreme drought years (Houghton et al., 2000), and estimates from the 1997–98 El Niño were of emissions between 0.81 and 2.6 Pg C $year^{-1}$ from tropical peat fires, 0.024–0.165 Pg C $year^{-1}$ from Amazonian fires, and 0.005 Pg C $year^{-1}$ in Mexico (Alencar et al., 2006; Cochrane, 2003; Page et al., 2002).

Fire intensity and resulting tree mortality are much higher in humid tropical forests when fires enter forests that are already heavily degraded by logging or previous fires (Cochrane, 2003). This is particularly problematic where forests have been affected by predatory or poorly managed logging practices, as the extensive canopy damage increases forest flammability (Holdsworth and Uhl, 1997; Ray et al., 2005). In addition, logging activities are often followed by an increase in human activities that can propagate ignition sources (such as slash-and-burn agriculture, charcoal production, and fires from people hunting or harvesting other forest products). Fire also threatens planned logging activities, including those supported in REDD+. Sustainable management of forests

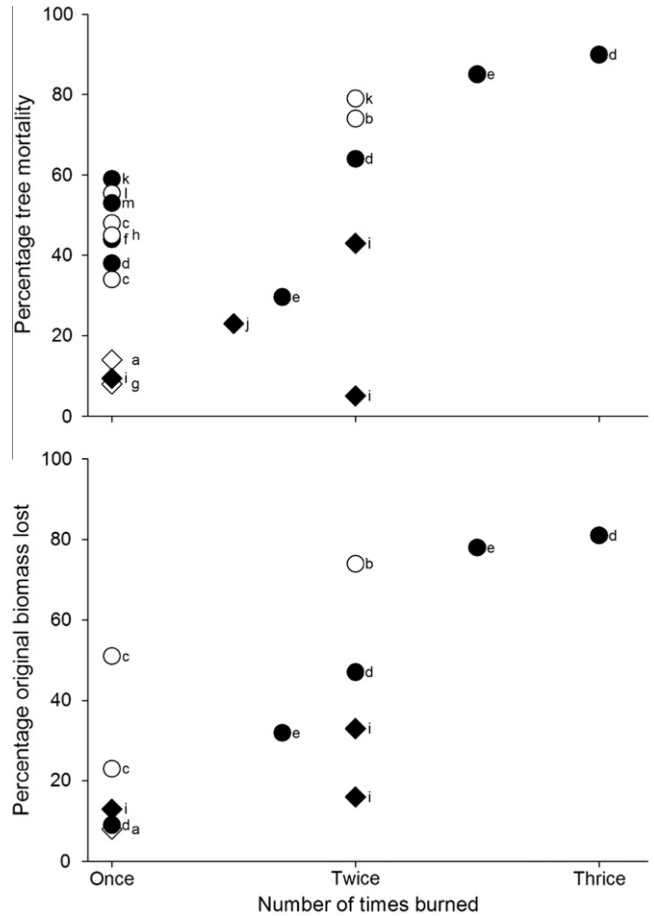

Fig. 1. Tree mortality (%) and biomass loss (%) recorded for stems ⩾10 cm DBH in 14 studies in humid tropical forests. Circles denote studies from evergreen humid tropical forests, and diamonds indicate studies identified by the authors as being transitional forests or sub-humid forests with greater seasonality. Black symbols denote sites that were logged prior to the fires, and clear denotes fires in undisturbed forests (or missing data). Given the limited sample size we do not attempt to take into account time since fire disturbance or logging, instead using the longest time since fire available in each study (ranging from 6 to 72 months). Fractional values for number of times burned represent studies where data from burn treatments were pooled. Studies are a = (Balch et al., 2011), b = (Barlow and Peres, 2004b), c = (Barlow et al., 2003), d = (Cochrane et al., 1999; Cochrane and Schulze, 1999), e = (Gerwing, 2002), f = (Holdsworth and Uhl, 1997), g = (IBAMA, 1998), h = (Kauffman, 1991), i = (Monteiro et al., 2004), j = (Pinard et al., 1999), k = (Slik and Eichhorn, 2003), l = (Van Nieuwstadt and Sheil, 2005), m = (Woods, 1989).

(SMF) is supported as a REDD+ activity to ensure that "*carbon stocks [in forests managed for timber] are maintained at least at constant levels on average over time*" (FAO, 2009). Although SMF is far more effective at conserving forest species than alternative silvicultural or agricultural production systems (Gibson et al., 2011), these additional benefits could be threatened by forest fires unless governance is sufficiently strong to minimise or contain these ignition sources while logged forests are regenerating.

Reducing forest fires becomes increasingly important for REDD+ activities if burned forests are unable to recover their original biomass faster than the average fire-return interval. Post-fire rates of carbon sequestration are poorly known, but existing evidence suggests fires cause a long-term reduction of forest biomass. First, large tree mortality continues for many years after fires take place (Baker et al., 2008; Barlow et al., 2003), and could continue for many decades (Barlow et al., 2010). Second, repeated fires may reduce the rate at which forests are able to accumulate carbon (Zarin et al., 2005). Third, the maintenance of carbon stocks is compromised by significant changes in species composition, with burned forests becoming dominated by pioneer species with low wood densities (Barlow and Peres, 2008; Cochrane and Schulze, 1999; Slik et al., 2010, 2002). These changes in composition are greatly exacerbated by repeated forest fires (Barlow and Peres, 2008) and could reduce the resilience of forests to other drivers of change, especially as lower wood density trees are more vulnerable to drought events (Chao et al., 2008).

Repeated forest fires also lead to functional deforestation, where fires are so intense they cause the mortality of almost all the above-ground live biomass, even though trees have not been cleared through felling (Fig. 2). Fire-affected forests can be classified as deforested by remote-sensing techniques. In eastern Amazonia, twice- and thrice-burned forests were 11 and 15 times more likely than unburned forests to be classified as being deforested (Cochrane et al., 1999). The confusion between fire-related functional deforestation and forest clearance presents challenges for measurement, reporting and verification (MRV) protocols in any REDD+ scheme involving avoided deforestation.

Regeneration of forests following deforestation and degradation is an important REDD+ activity. In one example, natural regeneration occurring across a 4.3 million ha region of the Peruvian Amazon represents an 18% offset against total gross emissions from land-use change and degradation (Asner et al., 2010). Furthermore, REDD+ based on regeneration is the only viable option in regions of the world with little primary forest remaining. Stickler et al. (2009) argue that the conversion of agricultural lands to forest regeneration will generally reduce the occurrence of fire, but this may be optimistic as regenerating forests are especially flammable (Ray et al., 2005) and could even increase the chance of transmitting fires to other land-uses. Clearly, fire reduction and control is essential in landscapes with active regeneration projects.

Fig. 2. Severe recurrent fire events can lead to functional deforestation, such as in this picture of forests burned in the dry season of 2007 in the municipality of Querencia, located in the state of Mato Grosso in the southern Brazilian Amazon. Photo: Jos Barlow.

2.2. Impacts of forest fires on REDD+ additional benefits: biodiversity

As well as meeting their primary target of emissions reductions, REDD+ schemes could also deliver important additional benefits by protecting biodiversity (CBD, 2011; Venter et al., 2009). However, without appropriate control, these benefits could be jeopardised by the significant and long-lasting impacts that forest fires have on tropical forest biodiversity. A number of studies on trees in the Amazon and South East Asia show that fires have long-term effects on the composition of the vegetation, with a consistent increase in pioneer species and loss of mature forest species (Barlow and Peres, 2008; Cochrane and Schulze, 1999; Slik et al., 2010, 2002). Birds are by far the best studied faunal taxa, and a synthesis of Amazonian data shows that low-intensity understorey fires can alter species composition more than selective logging, causing biodiversity changes similar to extreme forest fragmentation (1–10 ha isolated forest fragments) (Barlow et al., 2006). Fires also exacerbate the impacts of selective logging and fragmentation on biodiversity where both occur together, leading to significant species richness reductions of forest-dependent birds and large vertebrates in fragmented landscapes (Lees and Peres, 2006; Michalski and Peres, 2005).

Forest species recovery is slow after fire, and the avian species composition of burned forests can become less similar to that found in unburned forests over time due to lag-effects in biodiversity responses (Adeney et al., 2006; Barlow and Peres, 2004a). This occurs because bird species respond to changes in the structure and composition of the regenerating understorey vegetation, which resembles a young secondary forest in the first few years after a forest fire (Barlow and Peres, 2004b, 2008; Cochrane et al., 1999; Cochrane and Schulze, 1999). Impacts on biodiversity are observable 10 years after fires, and the relative abundance of disturbance-sensitive birds remains depressed in once-burned forests (Mestre, 2011).

Fire intensity and severity are much higher in previously-burned forests, due to the accumulation of downed woody material that becomes fuel (Cochrane et al., 1999) and the lower humidity levels resulting from the more open canopy (Holdsworth and Uhl, 1997). Recurrent forest fires cause most biodiversity of highest conservation concern to be lost, removing 72% of the bird species recorded in the understorey of unburned Amazonian forests (Barlow and Peres, 2004ab) and causing significant changes in species composition of birds in Sumatra (Adeney et al., 2006) and butterflies in Borneo (Cleary, 2003). Consequently, few immediate biodiversity benefits would be gained by protecting heavily degraded forests from future fires. However, longer-term benefits may exist if these forests recover carbon and some biodiversity over decadal time-scales, if restoration schemes can speed recovery, or if these forests help provide connectivity for forest biodiversity at a landscape level (see Gardner et al. same edition).

2.3. Impacts of forest fires on REDD+ co-benefits: human health and livelihoods

Forest fires have negative consequences for human health and livelihoods. During extreme drought events, extensive and long-lived smoke clouds increase respiratory illnesses, causing many lost working days and thousands of deaths (Kunii et al., 2000), in addition to disrupting air traffic and damaging other infrastructure (de Mendonca et al., 2004; Varma, 2003). The 1997–1998 El Niño-Southern Oscillation-related fires are estimated to have cost between $6.3 and $20.1 billion in Indonesia alone (Tacconi, 2003; Varma, 2003) and $10–15 billion across the Latin American tropics (Cochrane, 2003). Escaped fires can be very costly at the local level, causing losses of crops, livestock and farm infrastructure (Cochrane, 2003; Vera-Diaz et al., 2002) that are often overlooked in official damage estimates. In the case of cattle pastures, escaped fires can damage expensive fencing and force ranchers to rent additional pastures for livestock maintenance while pastures recuperate (Vera-Diaz et al., 2002).

Forest fires also have longer-term impacts for livelihoods. High levels of tree mortality (Fig. 1) mean that burned forests have less timber suitable for extraction, and post-fire changes in species composition favour pioneer species with little economic value (Barlow and Peres, 2008; Gerwing, 2002). Furthermore, the value of the surviving trees can be reduced by fire damage, and irregular fire-damaged stems are common in forests many decades after fires (Barlow et al., 2010). Forest fires also lead to declines in valuable non-timber forest products (Nygren et al., 2006; Sinha and Brault, 2005), which make important contributions to rural livelihoods (Koziell and Saunders, 2001). For example, in Amazonia forest fires caused a reduction in the abundance of *Attalea* palm trees used for thatch and lianas used for building, a loss of commercially-important fruits (Shanley, 2000) and the depletion of some game species (Barlow and Peres, 2006b). Although the dense post-fire regeneration of pioneer species may actually increase browsing ungulate abundance (Parry et al., 2007), increased understory density simultaneously reduces hunting efficiency (Barlow and Peres, 2006b; Parry et al., 2009).

3. Incorporating effective fire management into REDD+: the key challenges

The previous section demonstrated why forest fire prevention is fundamental to the success of REDD+ in humid tropical forests, helping guarantee the permanence of carbon stocks, reducing risks inherent in forest regeneration projects and the sustainable management of forest timber, preventing biodiversity loss, and protecting the livelihoods of forest-dependent people. However, as with other aspects of REDD+, achieving these benefits depends upon successful implementation (Blom et al., 2010; Borner and Wunder, 2008). Here, we examine the key challenges involved with incorporating fire avoidance into REDD+, first assessing whether avoided deforestation alone can help reduce the prevalence of fire in tropical forest landscapes.

3.1. Will avoided deforestation reduce the risk of fire in remaining areas of forest?

If efforts to avoid deforestation also guarantee a reduction of forest fires, implementation of specific interventions under the REDD+ activities for fire may not be necessary. There is reason for optimism, as reducing deforestation is likely to (i) reduce fragmentation rates, yielding fewer new forest edges that dry faster than forest interiors and are more prone to burning (Alencar et al., 2006; Cochrane and Laurance, 2002); (ii) reduce agricultural fire use, if intensive agriculture is favoured over extensive agriculture (Angelsen, 2010) and (iii) help prevent reductions in regional rainfall (Andreae et al., 2004; Eltahir and Bras, 1996).

However, empirical data from Brazilian Amazonia suggests more complex relationships between deforestation and fire. A basin-wide assessment of fire and deforestation showed that deforestation reduction does not always lead to a reduction in fire (Aragão and Shimabukuro (2010a). Between 2000 and 2007, fire occurrence actually increased in 59% of areas experiencing reduced deforestation. These counter-intuitive findings have multiple potential explanations (Balch et al., 2010). In part, deforestation only tends to slow down once a landscape is highly fragmented and the remaining forests are highly degraded: deforestation may have stopped, but the landscape still contains many fire-prone forest edges adjacent to fire-dependent agriculture (Aragão and Shimabukuro, 2010a,b). However, they may also reflect a short-term pulse in fire-use during the implementation phase of mechanization, when remnant stumps and roots are bulldozed into lines and burned (Morton et al., 2006). The fires could also correspond to the clearance of secondary forests that does not count as 'new deforestation'. Whatever the cause, it cannot be assumed that avoided deforestation will necessarily bring about an immediate reduction in fire, and carbon credits from avoided deforestation could be partially or completely negated by increased fire emissions from remaining forested areas (Aragão and Shimabukuro, 2010a). Furthermore, it is important to recognise that proposed amendments to laws controlling private reserves in the Amazon could lead to higher levels of deforestation and increased forest fragmentation in the near future, increasing the vulnerability of this region to fire (Sparovek et al., 2010).

3.2. Reducing the threat from agricultural fires

Most tropical forest fires are caused by agricultural fires escaping into surrounding vegetation (Uhl and Buschbacher, 1985), and reducing their prevalence requires an improvement in the management of agricultural fires, or their substitution by fire-free agriculture (Denich et al., 2005). Improved management of agricultural fires can be achieved through training or enforcing legislation, and some REDD+ type projects are already being used to modify the behaviour of smallholders. Peskett et al. (2011) outline an example where REDD+ payments provide incentives for local people in Uganda to maintain 100 m forest buffers around a reserve, therefore helping protect it from fire. The Kalimantan Forests and Climate Partnership combines incentive-based rewards to communities that prevent agricultural fires from being set in high risk weather periods, with a longer-term strategy that encourages alternative livelihoods that are not fire dependent (Anon, 2009). However, these efforts need to overcome the fundamental tension between the risk of fires escaping into surrounding forests and a farmer's need for a hot and successful burn.

In the longer-term, REDD+ payments could provide the capital and technical investments necessary to facilitate the shift toward fire-free agricultural practices (Palmer, 2011), such as mechanized land preparation, slash-and-mulch, perennial agriculture (with less frequent land preparation requirements), or intensive pasture management (Eastmond and Faust, 2006; Tschakert et al., 2007). This may be achievable in established frontiers with higher levels of governance, but will be much more difficult to implement in younger and more active frontier zones where fire-dependent slash-and-burn agriculture is most common, where technology and non-fire alternatives such as mechanization are hard to deliver, and where landowners lack the secure land tenure required for effective payments (Hirsch et al., 2010). Furthermore, any agricultural intensification resulting from REDD+ could have important environmental impacts from the increased use of fertilizers and pesticides.

It is imperative that REDD+ activities avoid negative social impacts and ensure positive outcomes for local people (Anon, 2011; Melick, 2010; Richards and Panfil, 2011). Altering agricultural fire management, or encouraging the switch to non-fire agriculture, is extremely sensitive, as fire provides a labour-saving method of land-preparation in the short-term, and is culturally embedded within many societies. Moreover, smallholders engaging in slash-and-burn agriculture are among the poorest people in rural tropical forest landscapes (Hirsch et al., 2010), and although they could benefit from REDD+ payments, they may also be vulnerable if projects impose new land management practices that are inappropriate in terms of their requirements for labour, capital, use of agrochemicals and technical assistance (Boerner et al., 2007), or reduce the availability of essential food items (Mertz, 2009). Socially inappropriate schemes could lead to widespread rejection of REDD+ activities (Eastmond and Faust, 2006), or create 'REDD refugees', where disaffected or unsuccessful smallholders migrate to forest frontiers or urban centres (Ghazoul et al., 2010).

3.3. Measuring, reporting and verification

In the context of REDD+, additionality refers to the extent to which any new intervention can reduce emissions and/or enhance carbon stocks above the business as usual scenario (reference level). Demonstrating additionality in REDD+ projects requires effective measuring, reporting and verification (MRV) (Angelsen, 2010; Anon, 2011; Baker et al., 2010; Miles and Kapos, 2008). In particular, investors and monitoring agencies need to map and monitor changes in tropical forest carbon stocks and emissions over large areas (Asner et al., 2010). There are some reasons to be optimistic that fire can be monitored effectively. Globally, MODIS and other satellites detect agricultural maintenance fires and fires in more open forests through the hot pixel product (Giglio et al., 2006). Within closed-canopy forests, sub-pixel mixture analyses that quantify the proportional components within each element of Landsat TM and ETM images have enabled creation of the Normalized Difference Fraction Index (NDFI) that can discriminate forest canopy damage caused by selective logging activities and forest fires (Souza et al., 2005). Similar fraction approaches have also been implemented on MODIS images (Shimabukuro et al., 2009). More recently, a Burn Damage and Recovery (BDR) algorithm based on combined Landsat and MODIS time series has enhanced identification of fire-related canopy damage from large-scale fires in transitional Amazonian forests (Morton et al., 2011), while Landsat has also been used to map a burn-scar index in the fragmented forests of the Eastern Amazon with 93% accuracy (Alencar et al., 2011). Recent technological advances with airborne LIDAR (light detection and ranging) has opened up new opportunities to quantify forest biomass in relatively focused forest regions (Mascaro et al., 2011). Yet despite the effectiveness of these products, we are still some way short of achieving systematic protocols for detecting and monitoring fire damage across whole biomes: high levels of cloud cover above tropical humid forests often complicate analyses of satellite images (Carlson and Curran, 2009), understorey fires remain difficult to detect from MODIS hot pixels, and it is much harder to map relatively small fires in fragmented landscapes.

Monitoring of forest condition and carbon stocks could be effectively carried out at local or community levels (Danielsen et al., 2011; Fry, 2011). At a first glance, it seems that forest fire occurrence could be integrated into community forest monitoring: smoke is easily observed at the time of the fire, and post-fire regeneration and fire scars on trees mean that burned forests can be detected for many years after any fire event (Barlow et al., 2010). However, identifying sources of smoke requires careful triangulation which is likely beyond the capacity of most communities, and differentiating between management fires in agricultural land and forest fires would be difficult. In summary, uncertainty about the reliable monitoring of fire activity at relevant scales complicates the implementation of fire avoidance as a specific management intervention for delivering one or more of the REDD+ activities. However, this should not distract from its importance: if fire management or avoidance is not considered as a valid intervention under one or more of the stated REDD+ activities for achieving emissions reductions, it is likely to be relegated to the context of REDD+ safeguards (as elaborated under Appendix 1 of the Cancun Agreements), which implies it would become subject to a much less rigorous and stringent assessment as part of the safeguard information systems (instead of MRV accounting for emissions reductions themselves).

3.4. Predicting the unpredictable? Temporal and spatial variation in fire

REDD+ functions by awarding payments for reductions in carbon emissions over time, as measured against business as usual scenarios (Angelsen, 2010). Future deforestation is very difficult to forecast (Corbera et al., 2010), but predicting fire risk may be even harder as it is dependent on interactions between anthropogenic and climatic factors. For example, although fire is a seasonal process in Amazonia (Aragão et al., 2008), its extent and frequency is vastly increased by severe droughts caused by El-Niño events (Timmermann et al., 1999), changes in Atlantic sea surface temperatures (Marengo et al., 2008), or from longer-term reductions in rainfall from global warming or land-use change (Malhi et al., 2009). However, there is some evidence of progress in this field, as recent modelling of the Oceanic Niño Index and/or Atlantic sea surface temperatures suggest abnormal Amazonian fire activity can now be predicted with a 3–5 month lead time (Chen et al., 2011; Fernandes et al., 2011).

Temporal and spatial complexities of fire occurrence also have important implications for REDD+ payments aimed to reduce its prevalence. Payments would be more effective, and ensure greater additionality, if they were higher in extremely dry years or in the most drought-affected regions, where the marginal benefits of effective fire management are much greater, and lower in years with less severe dry seasons, or regions where forests have not passed the flammability threshold. However, organising such a payment structure goes against the principle that payments for ecosystem services should guarantee sustained income in order to be successful (Hall, 2008), and demonstrates that the effective integration of fire reduction into REDD+ will require new approaches.

3.5. Which forests to target?

Forested regions with a high risk of fire can be identified through large-scale remote sensing analyses (Carmona-Moreno et al., 2005), but prioritizing fire reduction within regions is more complex. One approach would be to target heavily degraded and fragmented forests with the greatest probability of burning (Holdsworth and Uhl, 1997; Ray et al., 2005) and where fire prevention would enable natural regeneration to increase carbon stocks over time. However, there is a clear trade-off here as heavily degraded forests will have already lost most of their REDD+ benefits (carbon stock and associated biodiversity and livelihoods values), and it may be more effective to target REDD+ payments at relatively undisturbed primary forests that are much less likely to burn, but which have a high store of carbon, biodiversity, and timber. Although there is insufficient data available to quantify this trade-off, both strategies have their unique advantages and could deliver comparable levels of additionality depending on the socio-ecological context. Their relative cost-effectiveness could also depend on whether payments in individual countries or project areas prioritise maintenance of stocks or sequestration via regeneration, the ease of governance (protecting intact areas is much simpler than enforcing management changes in heavy populated areas), opportunity costs for the land that is targeted and the viability of effective monitoring.

3.6. Responsibility, liability and leakage

What happens to REDD+ payments if a forest burns? The loss of carbon stock from forest fires raises important questions about lia-

Fig. 3. MODIS hot pixels detected in 2009 in the Brazilian municipality of Paragominas in Eastern Amazonia. Hot pixels are strongly aggregated near agrarian reform settlements, which house some of the poorest and most vulnerable people in the municipality.

bility (Palmer, 2011), as protecting forests from fire is hugely complex and responsibilities are not always clear (Carlson and Curran, 2009). Ascertaining responsibility and liability at the property level is unlikely to work as ignition sources can be difficult to identify, and it is easy for landholders to deny responsibility since fires can almost always be blamed upon neighbours or people passing by the property. Furthermore, focussing solely on ignition sources imposes a narrow interpretation of liability, as different stakeholders may be jointly responsible when a forest burns. For example, while smallholders often produce most ignition sources (Fig. 3), it is the timber enterprises that reduce the flammability thresholds of forests by logging (Holdsworth and Uhl, 1997; Ray et al., 2005).

Leakage can occur if a REDD+ project displaces forest clearance or degradation activities to an area beyond the project focus. Leakage is also possible if REDD+ incentivizes fire-free agriculture in a region, but pushes smallholders and cattle ranchers further into the forest frontier – both encouraging deforestation, and putting fire-dependent agriculture into direct contact with previously undisturbed forests. The complexities of leakage and liability mean that attempts to incorporate fire reduction into REDD+ should work across whole landscapes (i.e. the national or state level instead of project based programs) instead of on individual properties, with performance and payments evaluated at community, county, state or country levels (such as the UNFCCC REDD+ scheme). Larger-scale projects also facilitate monitoring, contract design and enforcement, and enable reference level setting (Angelsen, 2010; Olander et al., 2011).

4. Conclusions

Forest fires are one of the most important forms of tropical forest degradation due to the predominance of fire-dependent agriculture, and increases in forest flammability caused by intensive logging practices, fragmentation and climate change. Given the scale of this threat, reducing the risk of forest fires is necessary to achieve the central REDD+ objective of securing and enhancing forest carbon stocks, as well as respecting key biodiversity and social safeguards. Achieving this fire reduction presents many challenges, especially as it will require changes in agricultural practices that take place outside of the remaining forests, the development of monitoring and verification that covers whole biomes, and a very careful consideration of the livelihoods of rural people living in tropical forest landscapes.

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