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Economically viable forest restoration in shifting cultivation landscapes

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Abstract

Shifting cultivation is a predominant land use across the tropics, feeding hundreds of millions of marginalised people, causing significant deforestation, and encompassing a combined area of land ten-fold greater than that used for oil palm and rubber. A key question is whether carbon-based payment for ecosystem services (PES) schemes can cost-effectively bring novel restoration and carbon-sensitive management practices to shifting agriculture. Using economic models that uniquely consider the substantial area of fallow land needed to support a single cultivated plot, we calculated the break-even carbon prices required for PES to match the opportunity cost of intervention in shifting agriculture. We do so in the North-east Indian biodiversity hotspot, where 35.4% of land is managed under shifting agriculture. We found net revenues of US\$829.53–2581.95 per 30 ha when fallow area is included, which are an order of magnitude lower than previous estimates. Abandoning shifting agriculture entirely is highly feasible with break-even prices as low as US\$1.33 t⁻¹ CO₂, but may conflict with food security. The oldest fallow plots could be fully restored for US\$0.89 t⁻¹ CO₂ and the expansion of shifting agriculture into primary forest halted for US\$0.51 t⁻¹ CO₂, whereas abandoning short-fallow systems would cost US\$12.60 t⁻¹ CO₂. A precautionary reanalysis accounting for extreme economic uncertainty and leakage costs suggests that all interventions, excluding abandoning short-fallow systems, remain economically viable with prices less than US\$4.00 t⁻¹ CO₂. Even with poorly formed voluntary carbon markets, shifting agriculture represents a critical opportunity for low-cost forest restoration whilst diversifying income streams of marginalised communities across a vast area.

1. Introduction

Shifting cultivation dates as far back as 10 000BC (Thrupp *et al* 1997) and remains the predominant agricultural land-use in many tropical regions, including much of Central and South America, Sub-Saharan Africa, and key areas of conservation interest in Asia and Australasia, notably Bangladesh, Laos and Papua New Guinea (Schmidt-Vogt *et al* 2009, van Vliet *et al* 2012, Heinimann *et al* 2017). Estimations predict at least 260 Mha is currently under the shifting cultivation mosaic (Silva *et al* 2011, Heinimann *et al* 2017), more than ten-fold greater than the combined area currently used for oil palm and rubber cultivation (Pirker *et al* 2016, Chiarelli *et al* 2018). This mosaic landscape is characterised by a cycle, with a cleared area cultivated for a short period of

time (<4 years) and larger areas then left fallow to recover secondary growth of various ages for a prolonged period (up to 30 years). Thus, while numerous patches recover during the fallow period, the rotation cycle continues, with a plot always under cultivation (Conklin 1961). The sheer scale of shifting cultivation means that vast stocks of carbon are released annually during the clearing and combustion of secondary growth. Total emissions are estimated at between 0.741 and 2.764 Gt CO₂ yr⁻¹, with an uncertain proportion of this returned to soil and biomass as fallow regrowth (Seiler and Crutzen 1980, Silva *et al* 2011).

Global economic and infrastructural trends are facilitating transitions from subsistence shifting cultivation to more profitable permanent crops or plantations as community isolation reduces, enabling wider market access (van Vliet *et al* 2012, Dressler

et al 2017), but driving carbon losses (Borah *et al* 2018). Where the practice remains, food insecurity and population growth are driving shorter cycle lengths (5 years or less) as smallholders demand more output from a limited land area. Where such contractions occur, carbon losses are also assured (Borah *et al* 2018), as the standing secondary forest growth in the eldest fallow plots is replaced with degraded scrubland characteristic of short cycles, limiting both biomass and biodiversity recovery (Blankespoor 1991, Itioka *et al* 2014). Such changes, both current and predicted, highlight this ancient practice will likely be replaced before the centuries end (Heinimann *et al* 2017, Dressler *et al* 2018). This also comes at the cost of forested area, carbon stocks, cultural practices, and food security for marginalised poor communities. If not re-sequestered in secondary fallow growth, the practices yearly clearing alone would account for 13.7%–51.2% of all agricultural CO₂ emissions worldwide (Seiler and Crutzen 1980, Silva *et al* 2011, Tubiello *et al* 2013).

With limited funding for global conservation efforts (McCarthy *et al* 2008, Mccarthy *et al* 2012), a key question is whether carbon-based payment for ecosystem services (PES) schemes can cost-effectively enable novel restoration and management practices leading to sustainable carbon enhancements within shifting agriculture whilst also meeting the nutritional needs of local people. Novel PES schemes should target locations where a trifecta of positive outcomes for carbon, biodiversity and society (e.g. food security and poverty alleviation, given the populace of most targeted systems compose mainly low-income groups or subsistence cultivators (Bellassen and Gitz 2008, Gilroy *et al* 2014a, Poudyal *et al* 2016)) can be achieved, maximising conservation impact, seller motivation, and longevity (Salzman *et al* 2018). Within shifting cultivation there is potential for this trifecta (Mukul *et al* 2016a, 2016b). Under carbon-based PES schemes, such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation), approaches could include abandoning the practice entirely, sparing the oldest secondary growth from the cultivation cycle, sustainably intensifying the practice, or preventing its expansion into primary forest.

Studies suggest that the per hectare revenue of shifting agriculture ranges from US\$440.00–623.00 ha⁻¹ yr⁻¹ in Cameroon (Kotte-Same *et al* 2001, Bellassen and Gitz 2008) and US\$801.16 ha⁻¹ yr⁻¹ in Bangladesh (Rasul and Thapa 2006). However, previous economic studies have not considered the vast area of fallow land needed to support each plot of cultivated land (Bellassen and Gitz 2008). In doing so, they may have overestimated the per hectare revenue of the practice, especially in the context of PES, which would be applied across the whole system. There is thus an urgent need to fully consider the heterogeneous

mosaic of land types in accurately assessing its economic returns and thus potential for cost-effective PES schemes. While the Stern Review and subsequent studies (Stern 2007, Kindermann *et al* 2008) triggered hope that carbon prices as low as \$5.00 t⁻¹ CO₂ could prevent significant deforestation, subsequent analyses have found that many tropical land uses remain too profitable to be widely impacted by such prices (Butler *et al* 2009, Fisher *et al* 2011a, Warren-Thomas *et al* 2014). By shifting the focus to marginally profitable and subsistence land uses, which still cover vast tracts of land, there remains hope that low prices may yet gain traction and yield lasting impact for the environment and cash-poor communities.

Here, we investigate the potential of different management scenarios to offer cost-effective protection or recovery of carbon stocks within shifting agriculture. Using economic data from the North-eastern Indian states, where shifting agriculture is responsible for up to 23% of annual forest loss (Murthy *et al* 2013, Pareta 2013), we analysed the opportunity cost of six intervention scenarios within existing 30 and 5 year cycles, and at-risk primary forest. We then simulated each scenario's potential carbon additionality over the project length. Finally, using three carbon accreditation methodologies, we modelled the required carbon break-even prices under each scenario to assess economic feasibility.

2. Methods

2.1. Focal area and data

We focus on Northeast India, an ideal potential site for PES schemes due to the secure legal tenure that is bestowed upon tribal communities and isolated smallholders practising shifting cultivation under the Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006 (Bhullar 2006, Ramnath 2008). Land tenure security is crucial for smallholders to engage with PES schemes, and despite controversy, the 2006 Act has already been used to facilitate a community's involvement in India first REDD+ project (Poffenberger 2015). Agricultural and economic data was drawn from all eight states within the region (supplementary methods, supplementary tables 2 and 3 (stacks.iop.org/ERL/15/064017/mmedia)). Carbon accumulation and stock data was obtained from a previous study focusing on three districts within Nagaland (Kiphire, Phek and Kohima) that typify shifting cultivation landscapes across the entire region. Fallow lengths varied between 6–30 years in the region, with families cultivating an average area of 1.6 ha (Borah J R personal observation) plus an uncertain area under communal fallow. Such observations within the study region are consistent with wider trends found in Northeast India (Maithani 2005, Lungmuana *et al* 2017). All modelling and

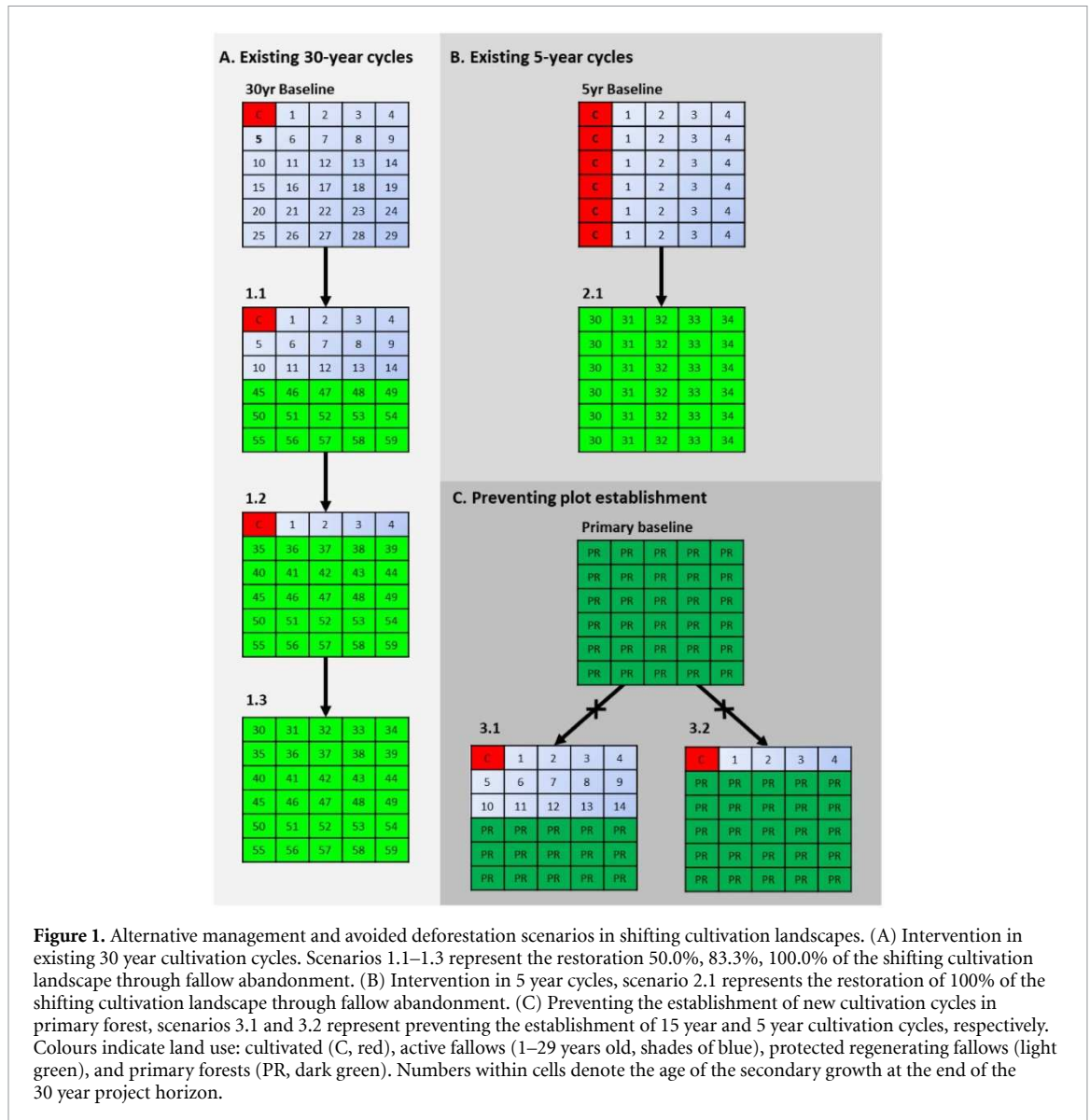


Figure 1. Alternative management and avoided deforestation scenarios in shifting cultivation landscapes. (A) Intervention in existing 30 year cultivation cycles. Scenarios 1.1–1.3 represent the restoration 50.0%, 83.3%, 100.0% of the shifting cultivation landscape through fallow abandonment. (B) Intervention in 5 year cycles, scenario 2.1 represents the restoration of 100% of the shifting cultivation landscape through fallow abandonment. (C) Preventing the establishment of new cultivation cycles in primary forest, scenarios 3.1 and 3.2 represent preventing the establishment of 15 year and 5 year cultivation cycles, respectively. Colours indicate land use: cultivated (C, red), active fallows (1–29 years old, shades of blue), protected regenerating fallows (light green), and primary forests (PR, dark green). Numbers within cells denote the age of the secondary growth at the end of the 30 year project horizon.

analyses were conducted using R 3.5.3 (R Core Team 2019).

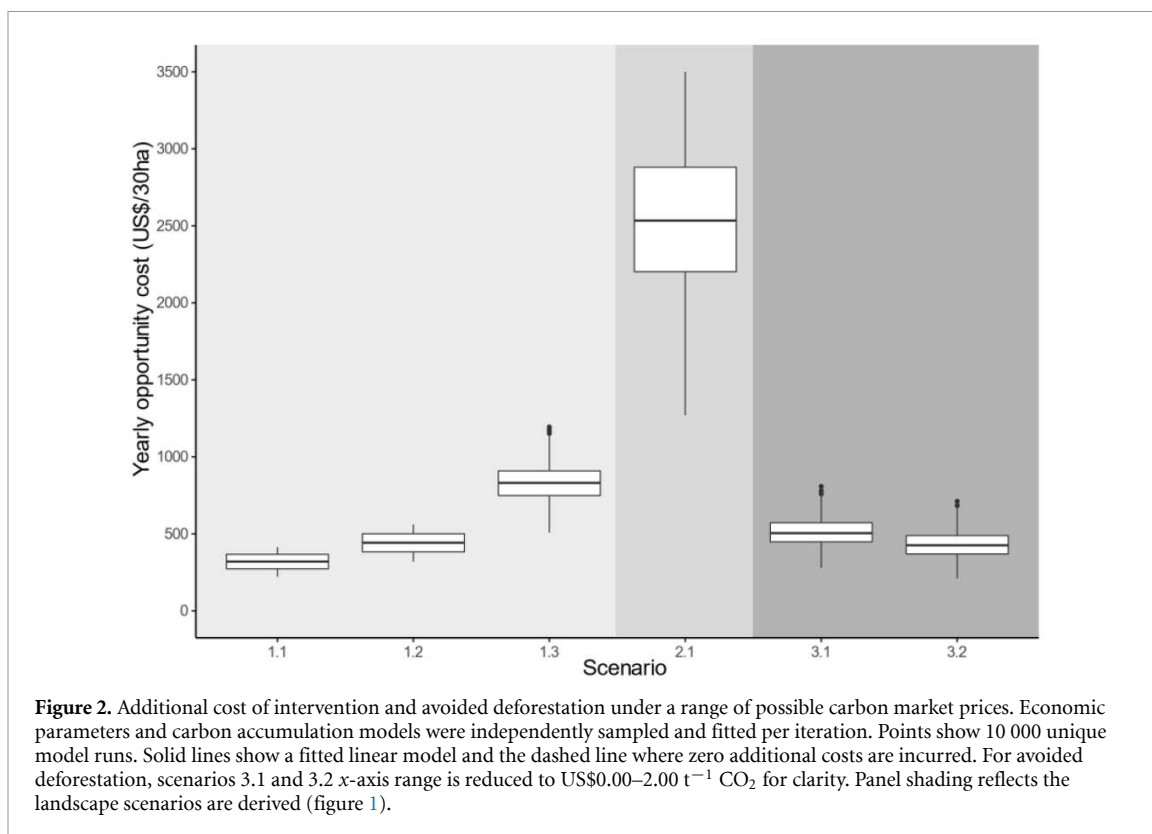
2.2. Management scenarios for modelling

To model plausible PES schemes, we considered three shifting cultivation landscapes: (A) scenario 1—existing 30 year cultivation cycles; (B) scenario 2—existing 5 year cultivation cycles; and (C) scenario 3—primary forest near existing settlements (figure 1). For existing 30 year cycles, scenarios 1.1 and 1.2 represent a contraction in fallow length to 15 and 5 year cycles, respectively, thereby facilitating the restoration of 50.0% and 83.3% of the fallow area. This assumes that fallow length contraction minimally impacts food security, with recent consensus favouring that once fallow increases beyond 2 years, yields are unchanged, with complete soil cohesion and nutrient composition recovery (Toky and Ramakrishnan 1981, Mertz 2002, Lungmuana *et al* 2017). Scenario 1.3 models the complete abandonment of the practice in favour of restoration. Within existing

5 year cycles, scenario 2.1 considers the complete abandonment of 5 year cycles. While cycles <5 years do exist, in shifting agriculture is practices in many regions (incl. Northeast India) with steep topography and intense wet seasons cause significant soil erosion and nutrient runoff, making such cycles unsustainable without significant anthropogenic input (Roder *et al* 1995, Tawnenga *et al* 1996, Shankar and Tripathi 1997). The complete abandonment of the practice at a landscape level is not culturally plausible and would likely decrease local food security and nutrition.

In primary forest landscapes, scenarios 3.1 and 3.2 model the prevention of 15 and 5 year cycles being established (figure 1). This protects 50% and 16.7% of the primary forest within each landscape that would otherwise be converted. As global trends favour transitions to reduced fallow lengths, the loss of primary forest to 30 year cultivation cycles was not considered.

A supplementary reanalysis was undertaken as a possible alternative to fallow area sparing through cultivation cycle contraction. We modelled cropping



for consecutive years to spare increasing proportions of the fallow area for restoration. Supplementary scenarios 1 and 2, respectively, introduced 2 and 4 year consecutive cropping, sparing 50.0% and 73.3% of the fallow area.

2.3. Economic modelling

To calculate break-even carbon prices, three novel economic models of the net present value (NPV; opportunity cost) of shifting cultivation were created (full details of each model given in supplementary methods and supplementary table 1). Variables included primary and secondary crop yields, crop prices, the area under cultivation, fallow growth area, non-timber forest produce value (NTFP), and labour and fertiliser costs. All economic parameters were inflation-adjusted to 2017 US\$. Uniquely, our analysis includes the area of fallow land needed for each hectare under cultivation and the minimal revenue this area generates. To simulate uncertainty and variation, normal distributions between the greatest and least values for all parameters were generated (supplementary methods and supplementary table 2). These values were independently sampled to generate 10 000 estimates of the opportunity cost for each management scenario.

2.4. Simulating carbon accumulation and breakeven price calculation

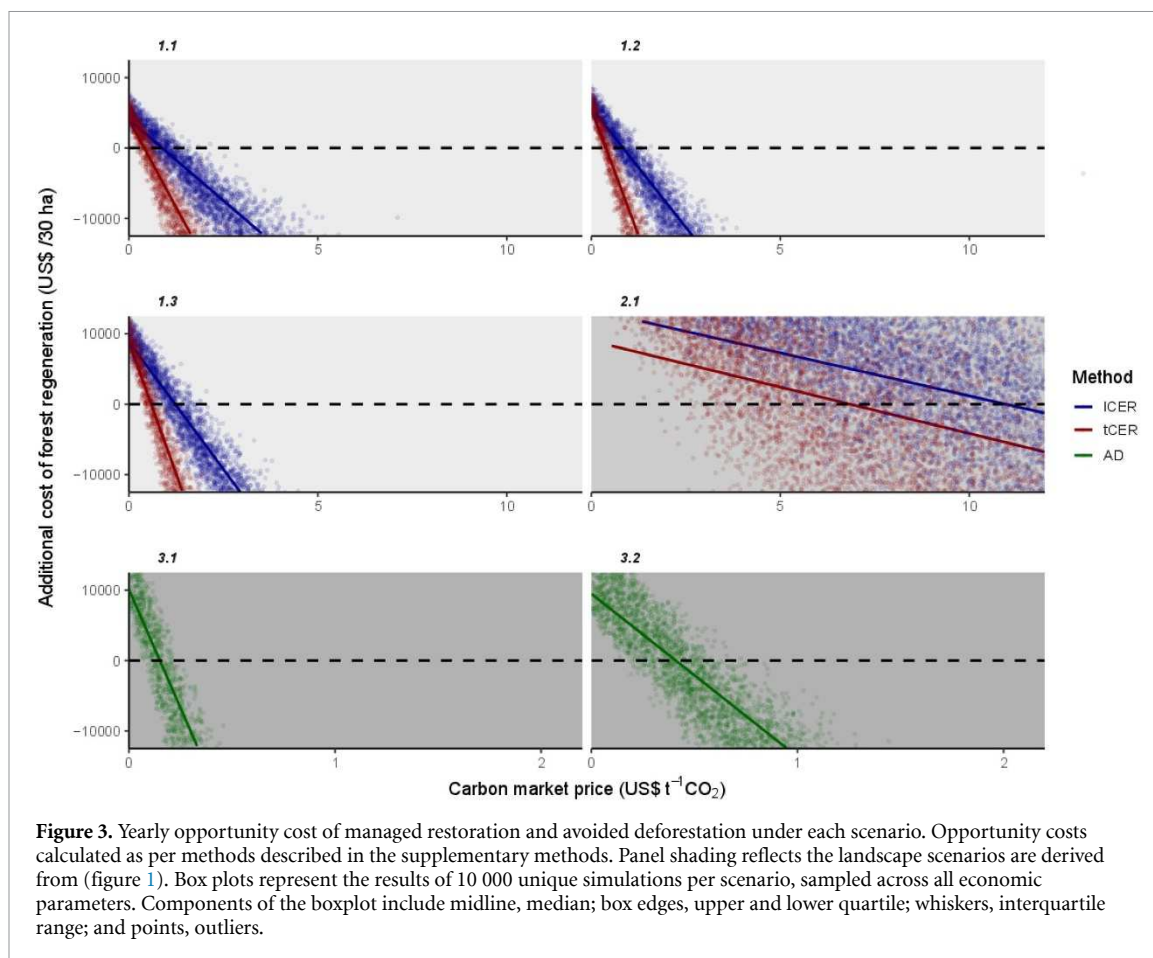
Carbon accumulation over the 30 year project length was predicted using a linear mixed-effects model examining the effect of secondary forest age on carbon storage, nesting sample squares within sample

landscapes as a random effect (see Borah *et al* 2018 for full details). For each scenario, carbon accumulation was modelled for each grid square over the full projected 30 year project length for 10 000 iterations. Through sampling with replacement, new datasets were created for each iteration and the model refitted to mimic variation in carbon sequestration rates (supplementary methods and figure S2). Further details on baseline carbon scenario creation and additionality calculations can be found in the supplementary methods.

Break-even carbon prices (US\$ t⁻¹ CO₂), under which implementing PES schemes are cost-effective, were calculated to offset both the opportunity cost of changes to the shifting cultivation and the total predicted costs of project monitoring and management (supplementary methods). Monitoring costs were extracted from existing community-based monitoring schemes (Cranford and Mourato 2011, Murtinho and Hayes 2017). Three accounting methods were used to calculate break-even price. For restoration-based scenarios (1.1–1.3 and 2.1), estimations used long-term certified emissions reduction schemes (ICERs) and temporary certified emissions reduction schemes (tCERs). For avoided deforestation scenarios 3.1 and 3.2, a modified avoided deforestation (AD) approach based on the carbon loss possible without intervention was used (supplementary methods).

2.5. Sensitivity analyses

The break-even prices needed are likely to be greater than those modelled when simply assuming costs to equal the opportunity, monitoring



and implementation costs (figure 2). Leakage has a significant impact on projected costs (Fisher *et al* 2011b, Gilroy *et al* 2014a, Jack and Cardona Santos 2017), but is often not incorporated in studies. Similarly, quantifying an exact discount rate for land uses disconnected from wider fiscal interactions remains unfeasible (Coller and Williams 1999, Halicioglu and Karatas 2011). A precautionary reanalysis doubled all opportunity cost values and allowed the discount to vary over a larger range (0.10–0.25). Similarly, an elasticity-based sensitivity analysis (*Elasticity index* $\sim U(1-4)$) discerned the impact of possible future changes in yield, price and additional costs, whilst allowing discount rate to vary between 0.10 and 0.25 (supplementary methods). Finally, cost-effectiveness was ascertained through a comparison of the break-even prices, incorporating leakage and economic uncertainty, and the additional carbon stocks accumulated by each scenario.

3. Results

3.1. Opportunity cost of conservation

Interventions in 30 year cycles had low opportunity costs (figure 3). Where 50.0% of the fallow was restored (scenario 1.1) mean costs were US\$239.52

per 30 ha. In scenario 1.2, where 83.3% of the fallow was restored, costs increased relative to scenario 1.1 by 45.7%, while in scenario 1.3, where cultivation was abandoned completely, mean opportunity cost was US\$829.53 per 30 ha, a 346.3% increase from scenario 1.1. Abandoning 5 year cycles (scenario 2.1) had the greatest opportunity cost of US\$2581.95 per 30 ha, further emphasizing the area under cultivation as the primary source of smallholder revenue. Mean opportunity costs of preventing the establishment of new cycles in primary forest (scenarios 3.1 and 3.2) were US\$605.98 per 30 ha for 15 year and US\$430.33 per 30 ha for 5 year cycles.

3.2. Required carbon break-even prices for viable conservation

Breakeven prices were low across all scenarios, but subject to considerable variation (figure 2). In existing 30 year cycles, increasing the area restored (50.0%, 83.3% and 100.0%) increased the required break-even price. Where 50.0% of the fallow land is restored (scenario 1.1), mean price under an ICER scheme was US\$0.96 $t^{-1} CO_2$ (tCER mean prices, US\$0.43 $t^{-1} CO_2$). Increasing the restored area to 83.3% (scenario 1.2) increased the mean price to US\$0.85 $t^{-1} CO_2$ under ICER (tCER mean prices, US\$0.40 $t^{-1} CO_2$) and to 100% (i.e. complete abandonment of cultivation; scenario 1.3), to a mean breakeven price

of US\$1.23 t⁻¹ CO₂ under ICER (tCER mean prices, US\$0.58 t⁻¹ CO₂).

Abandonment from 5 year cycles vastly increased breakeven prices to almost 10-fold that of abandoning 30 year cycles (figure 2), with mean prices under an ICER of US\$10.60 t⁻¹ CO₂ (tCER mean prices, US\$5.48 t⁻¹ CO₂). The large uncertainty in breakeven prices for abandoning 5 year cycles can be attributed to the multiple areas under cultivation and the high primary yield variation possible in the focal region, supported by the sensitivity analysis results highlighting the impact of variation in total yield on the final break-even price (supplementary methods).

Breakeven prices decreased as the area of primary forest protected from conversion increased. Preventing establishment of 15 and 5 year cycles in primary forest (scenarios 3.1 and 3.2, respectively) had mean break-even prices of US\$0.12 t⁻¹ CO₂ and US\$0.31 t⁻¹ CO₂ under an avoided deforestation methodology.

3.3. Sensitivity analysis

In existing 30 year cultivation cycles, break-even prices incorporating leakage and uncertainty in discount rates for scenarios 1.1, 1.2 and 1.3 under an ICER were US\$2.33 ± 0.73 t⁻¹ CO₂, US\$2.31 ± 0.72 t⁻¹ CO₂ and US\$3.58 ± 0.94 t⁻¹ CO₂, respectively (figure 4). These final prices are, respectively, 143.0%, 171.8% and 191.1% higher than scenarios 1.1–1.3 above (figure 2). Similarly, under a tCER scheme, prices were US\$1.33 ± 0.53 t⁻¹ CO₂, US\$1.32 ± 0.54 t⁻¹ CO₂ and US\$2.09 ± 0.94 t⁻¹ CO₂, respectively (figure 4).

Akin to the initial break-even price results, abandoning 5 year cultivation cycles has the greatest cost under an ICER scheme US\$37.92 ± 20.40 t⁻¹ CO₂ (tCER scheme price, US\$27.57 ± 19.38 t⁻¹ CO₂) when accounting for leakage and discount rate variation. Preventing the deforestation of primary forest to establish new cultivation cycles also remains a highly feasible proposition when simulated under variable future conditions. The mean carbon break-even prices were US\$0.73 ± 0.24 t⁻¹ CO₂ and US\$1.86 ± 0.60 t⁻¹ CO₂ under scenarios 3.1 and 3.2, respectively (i.e. reflecting the avoided establishment of 15 and 5 year cultivation cycles).

3.4. Cost-effectiveness of PES

Additional carbon stocks were greatest when 30 year systems were abandoned (scenario 1.3) or 83.3% of the fallow area was restored and removed from the cycle (scenario 1.2) (figure 5). Total landscape carbon stocks under these scenarios reached 98.4% and 84.3% of those found in primary forest, respectively (supplementary methods). Realistic break-even prices under these scenarios were low (<US\$4.00 t⁻¹ CO₂), highlighting them as optimal cost-effective interventions. Restoring 50% of the fallow area in 30 year fallow systems (scenario 1.1) resulted in the

second lowest additional carbon stocks but a break-even price of less than US\$2.50 t⁻¹ CO₂ (figure 5). However, total landscape carbon stocks under scenario 1.1 do reached 54.2% of that found in primary forest (supplementary methods). Abandoning 5 year cultivation cycles (scenario 2.1) accumulated significant additional carbon, but at the highest cost of all scenarios, rendering it economically unfeasible once leakage and uncertainty are accounted for (figure 5).

Avoided deforestation scenarios (3.1 and 3.2) accumulated the low additional carbon stocks (figure 5) but preserved the greatest carbon per hectare. Preventing the establishment of longer, 15 year cultivation cycles (scenario 3.1) protected a greater area of primary forest and yielded low required break-even prices when compared to the establishment of shorter 5 year cycles. Despite the low additionality in carbon stocking, the low cost of intervention to protect pristine primary habitats is highly economically viable.

4. Discussion

Shifting agriculture is a dominant land-use in many marginal areas of the tropics. Our results highlight that previous studies have overestimated revenues from shifting cultivation. Carbon-based PES schemes are highly cost-effective in long-fallow systems and primary forest landscapes. After accounting for leakage and economic uncertainty, shifting cultivation remains an excellent prospect for low-cost conservation.

4.1. Economics of shifting cultivation and PES

We found very low economic returns from shifting cultivation (US\$829.53 per 30 hectares per year in a 30 year fallow system), far lower than previous estimates of US\$151.28–1191.05 per single hectare in Bangladesh (Arifin and Hudoyo 1998, Rasul and Thapa 2006) and Cameroon (Bellassen and Gitz 2008). In only considering a single cultivated hectare, these studies overlooked the far larger mosaic of fallowed, reforesting land from which people obtain NTFPs. We valued these NTFPs, but their revenues are low (US\$11.13–20.70 ha⁻¹, Gundimeda *et al* 2005) relative to a hectare of cultivation. Additionally, we simulated economic returns from four secondary cash crops (e.g. chilli *Capsicum annum* and ginger *Zingiber officinale*) that are higher valued and cultivated over a small area compared to the low-profit staple crop. Previous work focused solely on staple crops (e.g. rice and cassava) and the comparatively small area of cultivated land (Arifin and Hudoyo 1998, Bellassen and Gitz 2008).

Carbon-based intervention in shifting agriculture landscapes was economically feasible, although considering leakage and economic uncertainty greatly increased break-even prices, highlighting the need for these additional analyses to avoid exaggerating

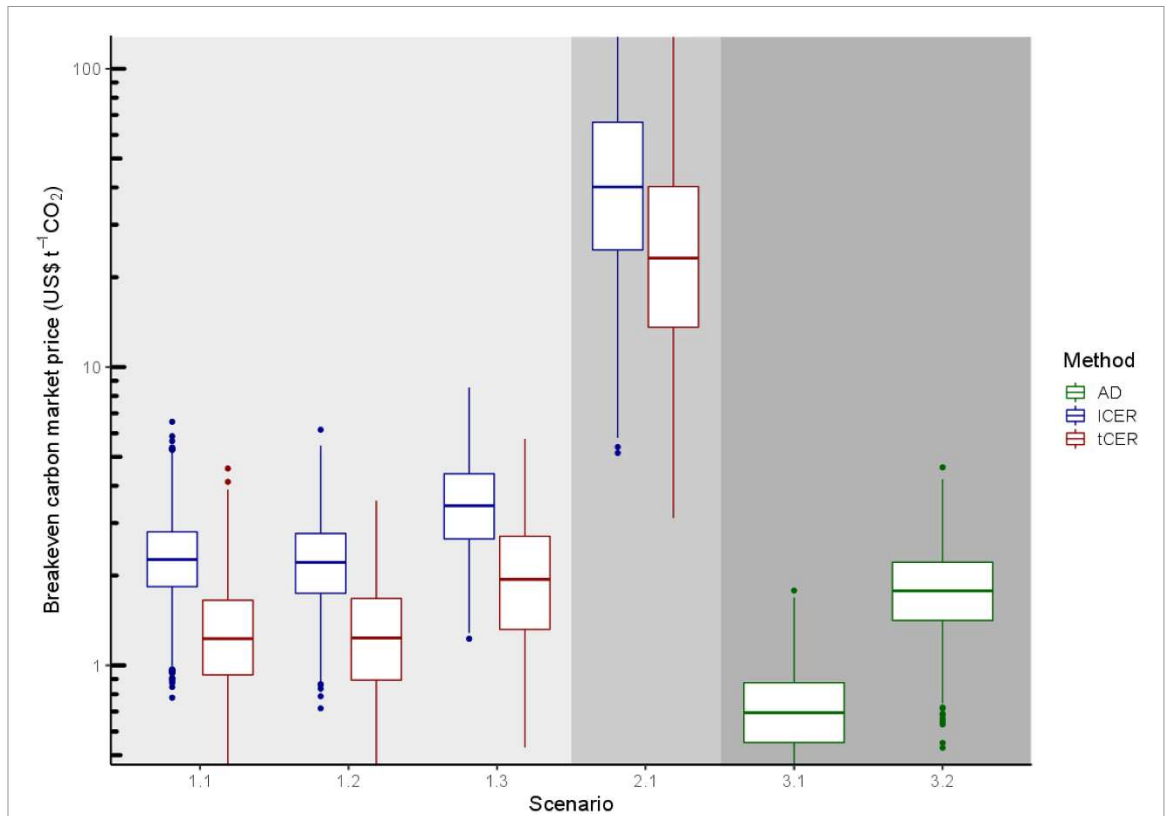


Figure 4. Cost-effectiveness of scenarios. Additional carbon stocks calculated from the difference between BAU baselines and modelled scenario stocks over the 30 year project length. Break-even prices incorporate leakage mitigation costs (doubling of scenario opportunity cost) and economic uncertainty (discount rate $\sim U(0.10-0.25)$). Vertical error bars denote the SD in breakeven price and horizontal error bars the SD in additional carbon from 10 000 simulation runs. Green shaded area denotes those with the lowest modelled break-even price and maximum carbon additionality. Black dashed and dotted lines represent EU ETS modelled prices of US\$30.22 $t^{-1} CO_2$ and US\$39.86 $t^{-1} CO_2$, in 2020 and 2030 (IETA 2019). The red long dash horizontal line represents the mean price of US\$3.50 $t^{-1} CO_2$ credits sold on the voluntary offsets market in 2017.

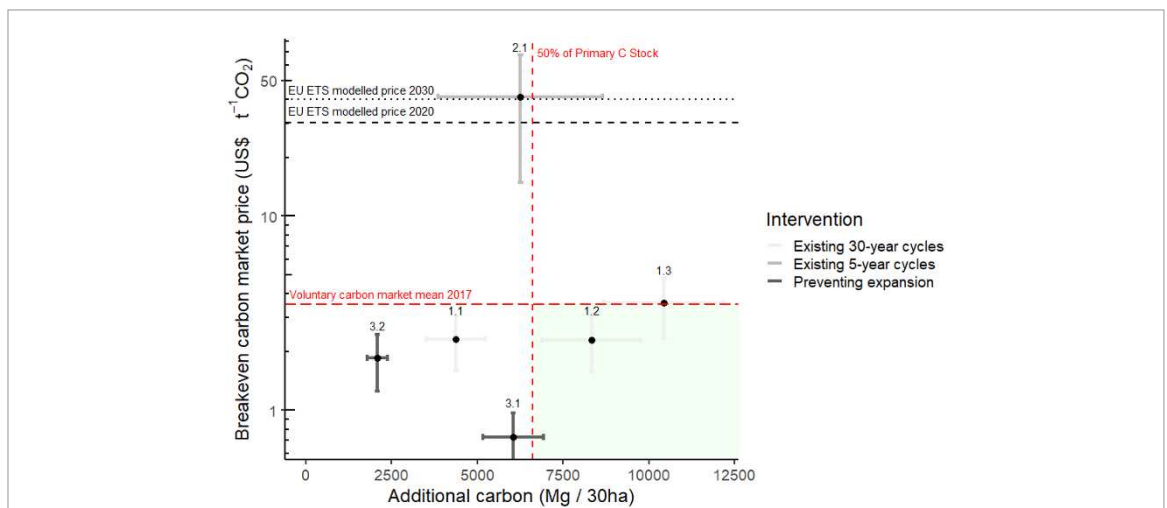


Figure 5. Simulated breakeven prices under all accounting methodologies incorporating leakage and discount uncertainty. Economic parameters and carbon accumulation models were independently sampled and fitted per iteration. Breakeven price calculations were adjusted to include a doubling of the opportunity cost of shifting cultivation per scenario and the discount rate allowed to vary uniformly between 0.10 and 0.25. Break-even prices were fitted to a log10 scale for clarity. Shades of grey denote the management Pathway (figure 1) and coloured borders, the accounting method used for each Pathway. Components of the boxplot include midline, median; box edges, upper and lower quartile; whiskers, interquartile range; and points, outliers.

the potential of schemes. Complete abandonment of 30 year cycles had the greatest carbon additionality and low break-even carbon prices that were comparable with other low-return practices, such as cattle

ranching (Gilroy *et al* 2014a). While abandoning 30 year cycles is economically feasible (and far more so than abandoning 5 year cycles) it may prove culturally unacceptable. Even in societies where shifting

cultivation is no longer the sole economic or nutritional mainstay, it is maintained to continue ancestral and cultural rituals (Ellen and Berstein 1994, Dressler *et al* 2018).

Preserving the practice with a reduced fallow length facilitates considerable aboveground biomass recovery and biodiversity co-benefits at low cost (Pawar *et al* 2004). In addition to restoration through fallow length constriction, a reanalysis incorporating cropping for consecutive years with fertiliser supplementation revealed sparing 50% (2 year cropping) and 73.3% (4 year cropping) of the fallow land yielded comparable prices of US\$3.45 \pm 1.05 t⁻¹ CO₂ and US\$2.64 \pm 0.86 t⁻¹ CO₂ under an ICER scheme, respectively (tCER mean prices, US\$1.99 \pm 0.79 t⁻¹ CO₂ and US\$1.53 \pm 0.62 t⁻¹ CO₂, respectively; see supplementary methods). Constricting shifting agriculture to a reduced area may trigger food insecurity (Ramakrishnan and Toky 1981, Toky and Ramakrishnan 1981, 1982), but recent work suggests that soil and yields recover within 2 years of abandonment (Lungmuana *et al* 2017), see also (Mertz 2002).

Constriction of fallow length and consecutive year cropping are forms of land sparing, allowing forest recovery in spared areas. Land sparing is the optimal strategy for landscape-level carbon stocking (Gilroy *et al* 2014b, Williams *et al* 2018) and biodiversity preservation (Phalan *et al* 2011, Luskin *et al* 2018, Cannon *et al* 2019). Additionally, there remains considerable scope for yield optimization within the system. Equitable yields in short-fallow systems have been achieved through ploughing and mulching burnt biomass into the soil (Kilawe *et al* 2018). Similar low-cost techniques have already been implemented successfully in localised communities in Northeast India (Shimrah *et al* 2015, Nath *et al* 2016).

The preservation of primary forests in Southeast Asia remains a conservation priority (Sodhi *et al* 2004). The low expected revenue of new cultivation cycles in combination with the high carbon stocks (Vashum *et al* 2016, Borah *et al* 2018, Salunkhe *et al* 2018) suggest a highly cost-effective route to prevent cycle establishment in primary forests. These costs are approximately 10- to 20-fold lower than those required to match the opportunity costs of preventing establishment of oil palm or rubber in the region (Fisher *et al* 2011a, Warren-Thomas *et al* 2018).

The diversity of economically viable approaches allows numerous scenarios to be implemented, addressing several ecological and socioeconomic issues simultaneously (Eloy *et al* 2012). The oldest cultivation cycles, furthest from village centres (O'Kelly and Bryan 1996) could be abandoned. Cultivation closest to community centres could be maintained, potentially via inputs, ensuring food security. Here, the oldest fallow plots could be spared clearing through fallow length constriction or cropping for consecutive years. This represents no loss of land under cultivation and restoration of up to 83.3% of

the fallow area. Where carbon-payments are delayed there is significant risk of leakage through clearing primary forest to establish new plots (Fu *et al* 2010, FAO 2015). Avoided deforestation scenarios could be implemented around communities, incorporating at-risk forests, and internalising leakage potential within the scheme itself.

By maintaining a comparable number of cultivated plots and partaking in a PES scheme as a community, smallholders can diversify their income streams and maintain cultural practices. Furthermore, as the risk of drought-induced yield losses increases with climate change (Das *et al* 2009, Gosling *et al* 2011), this additional income can be used to buffer smallholder's food security in a way not possible in solely subsistence livelihood systems. This also provides a transition period in which alternative economic activities that have been trialled with some success in region, such as agroforestry or fruit orchards, could be implemented (Singh *et al* 2016).

This study has three key caveats. Firstly, while the opportunity cost models account for five intercropped species, a single community in the Eastern Himalayas cultivated 72 staple and cash crop species (Yumnam *et al* 2011). Such diversity cannot be modelled with the limited data currently available. However, by including multiple crop species our study represents a significant enhancement from previous analyses (Rasul and Thapa 2006, Rahman *et al* 2007, Bellassen and Gitz 2008). Secondly, although implementing numerous scenarios simultaneously minimises any loss of cultivated plots, this analysis assumes complete markets where yields lost through scheme intervention, destined for smallholder consumption, can be bought from a functioning market system. This may limit applicability to settlements with poor infrastructural access to functioning markets. Thirdly, forest regeneration rates are likely to be affected by future climatic changes, with India projected to see increases in both temperature and precipitation (Gosling *et al* 2011). The integrated impacts of this on the regeneration of moist sub-tropical and montane landscapes prevalent in Northeast India and in turn on carbon pricing is uncertain, although warmer and wetter conditions could improve the rate of forest recovery and total carbon stocking further reducing breakeven carbon prices (Poorter *et al* 2016, 2019, Feng *et al* 2018).

4.2. Operationalising PES in shifting agriculture

The average price of credits sold on the voluntary market in 2017 was US\$3.50 t⁻¹ CO₂ (Hamrick and Gallant 2017), and prices ranged between US\$0.50–50.00 t⁻¹ CO₂, creating a competitive market for sellers (Newell *et al* 2013). For instance, at US\$4.50 t⁻¹ CO₂ (Jindal 2010), credits from a REDD+ pilot scheme in Mozambique were all sold successfully on the voluntary market. Direct restoration of the oldest fallow plots or restoration by

cultivating the same plot for consecutive years is thus economically feasible, while avoided deforestation is highly viable with modelled prices less than half of the market average.

Implementation must consider the potential for negative community responses, reduced employment opportunities and food insecurity derived from incomplete markets. The East Khasi Hills REDD+ project, the first of its kind in Northeast India (Katila et al 2014, Vijge 2015), upskills communities and employs members to monitor forests and complete carbon assessments (Poffenberger 2015). Replicating this would maximise participation and compliance with novel intervention strategies. Northeast India remains an excellent location for the further development of PES schemes. The recent inclusion of forest area into India's tax revenue distribution formula entails that States receive fiscal returns of up to US\$303 ha⁻¹ yr⁻¹ for forested land (Busch and Mukherjee 2017). Coupled with carbon-based PES schemes, forest restoration is beneficial at individual and state levels. Furthermore, the formal recognition of smallholder tenure in India (Bhullar 2006) reduces the potential for land tenure conflict, allowing smallholders the autonomy to manage their land independently.

Future projects within the region should learn from the East Khasi Hills REDD+ project, paying particular regard to the consideration given to existing community hierarchies and how quickly smallholders were upskilled to complete the carbon validation and certification process as an alternative income source (Poffenberger 2015). The additional income also facilitated the transition from low-grade free-grazing animals (e.g. goats) to penned chicken and pigs, further buffering local food security (Poffenberger 2014). By advocating community-led land management, such schemes have the potential to encourage low-cost conservation and to support local people in sustainable outcomes that protect cultural heritage whilst offering food security.

5. Conclusions

Shifting cultivation remains a predominant tropical land use, sustaining subsistence communities in remote and isolated areas. A diverse range of intervention scenarios are identified as viable under REDD+ and other carbon-based PES schemes, being extremely low cost and economically feasible, even in the face of weak voluntary carbon market demand. Such schemes could have a trifecta of co-benefits for stakeholders, increasing income and food security, landscape-level carbon stocks and biodiversity. Through abandonment, fallow restoration, and preventing plot establishment in primary forest, carbon-based PES schemes have the potential to address numerous conservation goals in a vast tropical land-use.

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Data availability

Any data that support the findings of this study are included within the article.

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