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Current trends of rubber plantation expansion may threaten biodiversity and livelihoods☆

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A B S T R A C T

The first decade of the new millennium saw a boom in rubber prices. This led to rapid and widespread land conversion to monoculture rubber plantations in continental SE Asia, where natural rubber production has increased >50% since 2000. Here, we analyze the subsequent spread of rubber between 2005 and 2010 in combination with environmental data and reports on rubber plantation performance. We show that rubber has been planted into increasingly sub-optimal environments. Currently, 72% of plantation area is in environmentally marginal zones where reduced yields are likely. An estimated 57% of the area is susceptible to insufficient water availability, erosion, frost, or wind damage, all of which may make long-term rubber production unsustainable. In 2013 typhoons destroyed plantations worth US$ >250 million in Vietnam alone, and future climate change is likely to lead to a net exacerbation of environmental marginality for both current and predicted future rubber plantation area. New rubber plantations are also frequently placed on lands that are important for biodiversity conservation and ecological functions. For example, between 2005 and 2010 >2500 km^2 of natural tree cover and 610 km^2 of protected areas were converted to plantations. Overall, expansion into marginal areas creates potential for loss-loss scenarios: clearing of high-biodiversity value land for economically unsustainable plantations that are poorly adapted to local conditions and alter landscape functions (e.g. hydrology, erosion) – ultimately compromising livelihoods, particularly when rubber prices fall.

1. Introduction

Hevea brasiliensis, the para-rubber tree, is the major source of natural rubber for the global annual production of >1 billion car, truck and aircraft tires (Li and Fox, 2012; WardsAuto, 2013). This rapidly expanding industry is driving land conversion to rubber plantations in SE Asia where 97% of the world's natural rubber is produced (FAO, 2013). Natural rubber prices are volatile and dependent on many factors. The decade between 2001 and 2011 saw a tripling of rubber prices. A slowdown in demand (particularly in China) combined with rising stocks due to widespread rubber planting has since led to subsequent price declines of over 70% (Fig. B.1). However, the global consumption of natural rubber is expected to continue to grow, and rising prices in the immediate future are likely (Prachaya, 2015). Alternatives to natural rubber are still limited as synthetic rubber produced from petroleum does not match its resilience, elasticity, and abrasion resistance (Cornish, 2001).

Rubber was historically planted in the equatorial zone between 10° and −10° latitude (Priyadarshan et al., 2005). However, many traditional rubber growing areas in insular SE Asia are being

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converted to oil palm, which is even more lucrative but strictly humid-tropical (Fox and Castella, 2013). This and China's success in growing hardy rubber clones led to an expansion of rubber into non-traditional planting areas all over continental SE Asia (Li and Fox, 2012; Priyadarshan et al., 2005). Rubber production in continental SE Asia has increased by almost 1500% from just over 300,000 tonnes in 1961 to over 5 million tonnes in 2011 (FAO, 2013). The vast majority of these new rubber plantations are mono-cultures as opposed to the traditional mixed rubber agroforestry systems in Indonesia (Feintrenie and Levang, 2009; van Noordwijk et al., 2012). While the original expansion was driven by state agencies, the sector is now dominated by small-holders in China, Vietnam and Thailand, as well as large-scale economic concessions in Cambodia, Laos and Myanmar (Fox and Castella, 2013). The crop has brought wealth to many poor areas (Qiu, 2009), however, socio-economic concerns arise from a host of issues, including rubber price fluctuations, narrowing of income sources, potential loss of food security, dependency on global markets of small-holders who often have little knowledge of the latter, and "land grabbing" practices (Fox and Castella, 2013; Fu et al., 2010; Xu et al., 2014). Conversion to rubber plantations also has environmental implications such as reduction in water reserves (Guardiola-Claramonte et al., 2008; Ziegler et al., 2009), carbon stocks (de Blécourt et al., 2013; Li et al., 2008), soil productivity (Zhang et al., 2007), and biodiversity (Li et al., 2007; Warren-Thomas et al., 2015).

An understanding of which environments rubber has spread to and whether rubber cultivation on them is sustainable, is vital for wise land use planning and policy interventions. Currently, a quantitative region-wide assessment of the environmental space occupied by rubber plantations is lacking, as are assessments of the rates and consequences of establishing plantations in novel environments. Here we (a) quantify the environmental space in which rubber occurs naturally; (b) establish the extent and trends of plantation spread into marginal environments; (c) assess the types of land that are being converted; (d) use this information to predict future patterns of land conversion, and finally (e) evaluate the biodiversity and socio-economic risks of land conversion to rubber plantations.

2. Material and methods

2.1. Model of historically suitable environments

We developed a global bioclimatic model of the environmental space where rubber would naturally occur ('historically suitable' space) based on the natural distribution of *H. brasiliensis*, and used this to identify where rubber is planted into novel environments. For this we obtained 97 geo-referenced and herbarium vouchered records (GBIF, 2013) of wild origin, which capture the range of environmental conditions the species occupies within its native range (Amazon Basin and Matto Grosso in Brazil, Guianas). To characterize the environmental space we acquired data on 31 topographic, climatic and substrate related environmental variables, which have been reported to directly or indirectly influence the suitability of habitat for rubber (Table B.1; 2.1.1). We then used a species distribution modelling approach, whereby the native rubber records were combined with environmental layers to produce a spatially explicit model of habitat suitability for rubber. We explored a range of modelling methods using the R library 'dismo' (Hijmans et al., 2013) of which MaxEnt (Phillips and Dudik, 2008) produced results that were closest to areas known to be historically suitable for rubber (Li and Fox, 2012; Priyadarshan et al., 2005), and response curves that were in closest agreement with existing literature on agricultural trials (Mokhatar et al., 2011; Nair et al., 2010; Priyadarshan, 2003a, 2003b, 2011; Priyadarshan et al., 2005; Rao et al., 1998). The final model achieved a mean Area Under Curve (AUC) of the receiver operating characteristic of 0.97 ($\pm$0.014 SD) under 10-fold cross-validation. Measures of confidence were derived by performing calculations on three thresholds for converting the continuous habitat suitability predictions into binary maps. For further details on the environmental variables, and model settings, selection, validation and performance see Appendix A.

2.2. Contemporary distribution of rubber plantations

The current distribution of rubber plantations in continental SE Asia was based on a map generated by Li and Fox (2012) using MODIS Terra 16-day composite time-series NDVI products spanning March 2009 to May 2010 at a resolution of 250 m. The available data cover the following areas: S China, all of Laos and Cambodia, most of Vietnam, N and central Thailand and S and E Myanmar (Fig. 1b). No data are available for the following areas: S Thailand, SW Vietnam and W Myanmar. When we use the term "continental SE Asia" we mean the entire region as delineated by country boundaries. Our definition of continental SE Asia does not include peninsular Malaysia. When we use the term "study area", we are referring to the rectangular area for which we have rubber distribution data. The available data differentiate between young ($<$4 years old) and mature ($\geq$4 years old) plantations. To test for scale-dependency of the results we further gathered high-resolution rubber plantation maps for Xishuangbanna, China for four time intervals: four Landsat TM/ETM images from 1988, 1992, 2002 and 2006 (spatial resolution c. 30 m), and 48 RapidEye images of level 3A captured in 2010 (spatial resolution c. 5 m) (Xu et al., 2014). To analyze whether there were significant shifts in the environmental niche rubber plantations occupied between 2005 and 2010 (respectively, in Xishuangbanna between 1988 and 2010) we followed a statistical framework developed by Broennimann et al. (2012), using default settings for the resolution of the environmental space (N = 10,000 grid cells), and the smoothing parameters of the kernel density function. In addition we undertook an analysis of environmental similarity between the natural *H. brasiliensis* range and the environments occupied by rubber plantations in mainland SE Asia by calculating a multivariate environmental similarity surface (Elith et al., 2010).

2.3. Characterization of novel environments

We trawled the academic literature, reports from governmental and non-governmental organizations, and local news sources for qualitative information and quantitative data on levels of rubber tree mortality and average annual yields in relation to environment. We then delineated and mapped generalized environmental thresholds to characterize the novel environmentally marginal space that rubber is being planted into, at three hierarchical levels:

Level 1. Novel marginal environments: this encompasses all environmental space that rubber is being planted into that is different from the historically suitable growing space.
Level 2. Sub-optimal marginal environments: a subset of level 1, where there are reports of environmental stresses reducing yields and/or the harvesting period, increased time to maturity and/or susceptibility to diseases.
Level 3. Risky environments: a subset of level 2 where environmental stresses are so severe that there is a risk of unsustainability – either due to reported high plantation mortality and/or evidence for negative feedbacks between

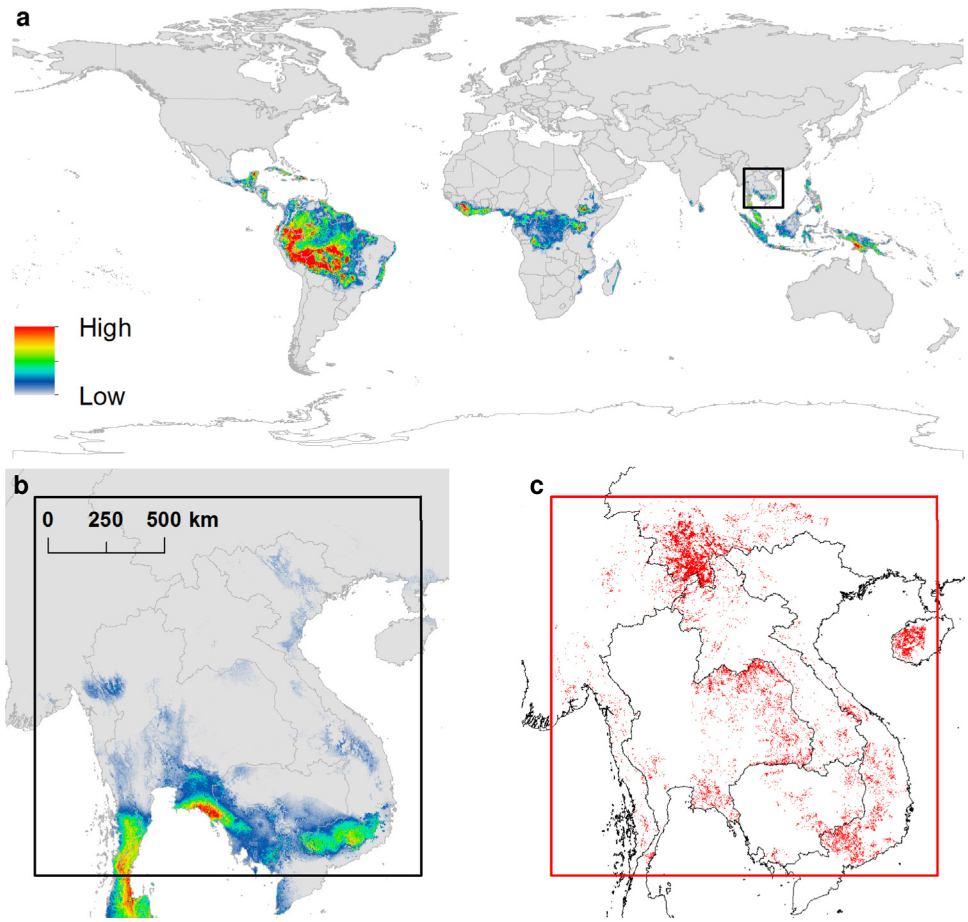

Fig. 1. Distribution of historically suitable environmental space for rubber. (a) Global distribution of historically suitable environmental space. (b) Distribution of historically suitable environments in continental SE Asia. (c) Location of the rubber plantations in the study area in 2010 (mapped at resolution of 250 m by Li and Fox (2012); map has 1 km spatial resolution for better visibility).

large-scale conversion to rubber and regional climate/landscape function.

Insufficient information was available to differentiate the tolerances of different specifically bred hardy rubber clones. However, given that planting in environmentally marginally areas typically involves the use of particularly hardy clones, our thresholds capture the ecological tolerances of such hardy clones.

2.4. Predictions of future rubber spread

To investigate whether the spread of rubber is predictable and which factors are most influential in explaining the spatial patterns we used Boosted Regression Trees (BRT) (Elith et al., 2008) to model the spread of plantations between 2005 and 2010. We included seven candidate predictors representative of environment and infrastructure: traditional habitat suitability, land cover type, presence of protected areas, and distances to the nearest plantation, road and major populated area (Table B.2). The dependent variable was binary (presence/absence of rubber plantations in 2010). We excluded cells where rubber had already been present in 2004/05 in all 250 × 250 m sub-cells, leaving N = 2,297,790 data points for the analysis. Given that individual countries may differ in their trajectories of rubber spread, we modelled the spread of rubber plantations for each of the six mainland SE Asia countries separately. For computational feasibility we repeatedly (N = 100) subsampled N = 10,000 data points for the analysis in a stratified random fashion. The models were developed at a 1 km resolution and the model settings for tree complexity, learning rate and bag fraction were optimized using 10-fold cross-validation. Further details on model settings, parameterization and performance are summarized in Table B.2.

2.5. Likely impact of future climate change

To explore whether predicted future environmental change is likely to ameliorate or exacerbate environmental marginality in areas where rubber is being planted we analyzed data from 39 models from the Coupled Model Intercomparison Project Phase 5 (Taylor et al., 2011) across four Representative Concentration Pathways (RCPs) for 2050. We calculated mean, minimum, maximum and standard deviation of change across all 39 models for the following variables: minimum precipitation in the driest month, maximum precipitation in the wettest month, number of months of <60 mm rainfall per month, minimum temperature in the coldest month, and number of months with a minimum temperature <0 °C. Subsequently, we assessed whether there is likely to be an exacerbation or mitigation in environmental stresses for existing and predicted future plantation area, and what proportion of the models agree on the direction of that change.

All analyses for this manuscript were conducted in R 3.0.1 (R Development Core Team, 2013) with the vegan (Oksanen et al., 2012), raster (Hijmans, 2013), dismo (Hijmans et al., 2013), maptools (Bivand and Lewin-Koh, 2013), rgdal (Bivand et al., 2013), spatstat (Baddeley and Turner, 2005) and gbm (Ridgeway, 2013) libraries.

3. Results

3.1. Distribution of historically suitable environmental space

The model of suitable environments for the original rubber tree predicts that there are c. 16 million km^2 (±3.8 million SEM) of historically suitable environmental space globally (Fig. 1a). The environmental tolerances indicated by the model are in agreement with existing literature on agricultural trials (Mokhatar et al., 2011; Nair et al., 2010; Priyadarshan, 2003a, 2003b, 2011; Priyadarshan et al., 2005; Rao et al., 1998): the species, in its original form, has limited tolerance to frost and high temperature seasonality, it requires at least 6 months in the year with rainfall >60 mm per month, it cannot withstand <20 mm rainfall during the driest quarter nor mean windspeeds of >4–5 m s^{-1}, and it favours areas with approximately 6 h of sunshine per day, and 27 °C during the rainy reason. Most of the historically suitable environmental space (60% ±5) is located in tropical South America where *H. brasiliensis* is native, but large-scale production is no longer commercially viable due to the occurrence of a fungal pathogen (*Microcyclus ulei*) (Priyadarshan et al., 2005) and higher costs of labour. Approximately 2 million km^2 suitable space is located in SE Asia, most of which occurs in Indonesia (65% ±1), the Philippines (11% ±1) and Malaysia (11% ±0.5). Despite almost 50% of the world's rubber being produced in continental SE Asia (defined here as Thailand northwards), the region has just 1.5% (c. 260,000 km^2 ±100,653 SEM) of historically suitable environmental space for rubber, of which most is located in Thailand (51% ±5), Vietnam (21% ±1) and Cambodia (16% ±5) (Fig. 1b). This modelled space overlaps largely with the areas in SE Asia where rubber was indeed planted and bred prior to the 1960s (Li and Fox, 2012).

3.2. Spread of plantations into marginal environments

A comparison of the distribution of rubber plantations (Fig. 1c) with the modelled distribution of historically suitable environmental space indicates that rubber plantations are rapidly spreading into not only novel but environmentally marginal environments (Table B.3). Prior to 2005 plantations were established in a wide range of climatic zones, including historically suitable and potentially sub-optimal environmental space (Fig. 2). Newer plantations (established 2005–2010) have spread predominantly into potentially sub-optimal environmental space (higher altitudes, steeper slopes, more frost, lower temperatures during the wet season and/or the coldest month of the year, and a longer dry season; Fig. 2). By 2010 a total of almost 19,000 km^2 (±581 SEM) plantations were located in novel marginal environments (89% ±3 of all plantations). This shift is statistically significant ($D = 0.534$; P [niche equivalency] ≤0.05), and niche similarity between young and mature plantations is almost no greater than random (P [niche similarity] $>0.05 \leq 0.1$). The largest environmental space shifts occurred in Myanmar, Vietnam and China (Fig. B.2); and the shift in the environmental space is statistically significant (niche equivalency and similarity tests following Broennimann et al. (2012); P values for all tests were ≤0.05). Higher-resolution and longer-term results for Xishuangbanna, China show that the increase in the breadth of

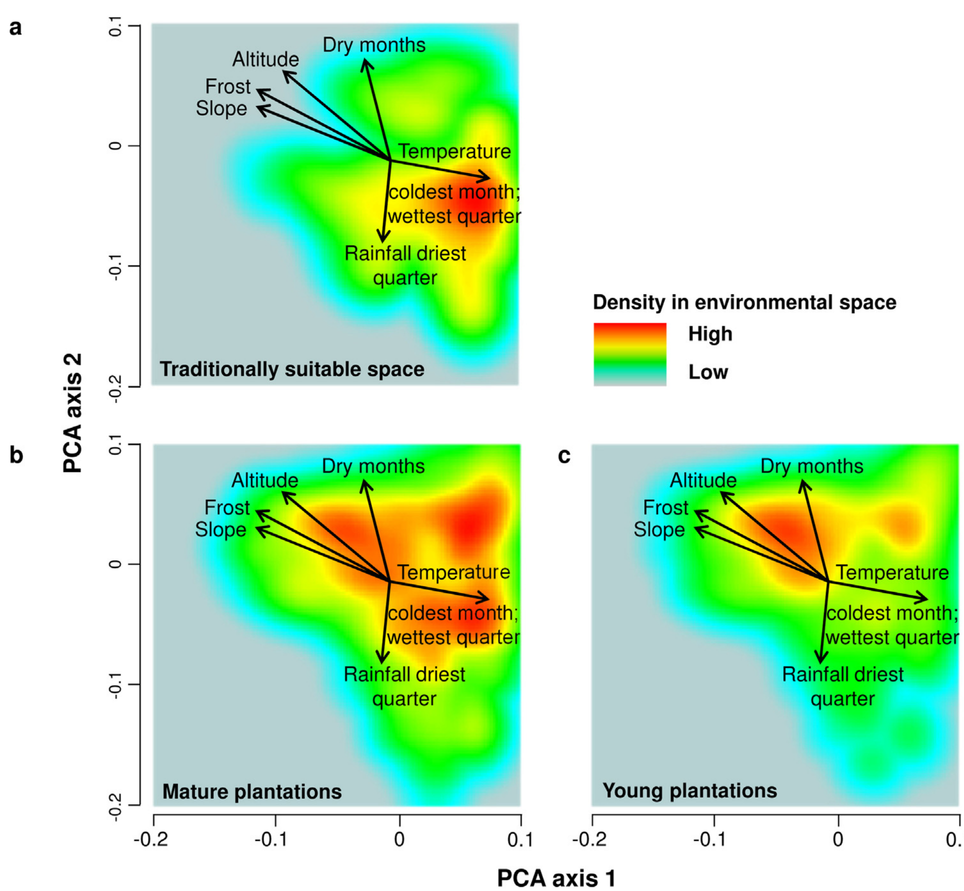

Fig. 2. Density of young and old rubber plantations in environmental space. The two-dimensional representation of environmental space was generated using a Principal Components Analysis of 15 environmental variables. The first and second axes explain 38% and 24% of the variance respectively. The PCA is centred and scaled to unit variance. Key environmental variables are shown as vectors, pointing in the direction of the gradient, with the length of the vector proportional to the variables' correlation with the ordination. For full list of correlations between the environmental variables and the first and second PCA axes see Fig. B.2. (a) Historically suitable environmental space. (b) Environmental space occupied by plantations established prior to 2005, and (c) environmental space of plantings between 2005 and 2010.

environmental space occupied by rubber is closely correlated with rubber price increases (Pearson's r correlation between niche breadth and price = 0.957; $P \leq 0.05$; Fig. B.3). The greatest shift to marginal environments began around 2002 when rubber prices began escalating.

Although rubber is produced successfully in some marginal environments – as many hardy clones have been developed – there are also numerous reports of failures associated with environmental stress in sub-optimal or marginal environments (Tables 1 and 2; Fig. 3). Areas where severe environmental stresses threaten sustainability include the following: (1) areas with frequent typhoons (typhoon risk zone); (2) areas >900 m altitude and/or on slopes >24° (topographic risk zone); (3) areas with >5 months <60 mm rainfall month^{-1} (drought risk zone); and/or (4) >10 days frost year^{-1} 1 (frost risk zone). Reduced yields are likely in areas with dry stress (>5 months <60 mm rainfall month^{-1}, and/or <1200 mm rainfall year^{-1}, and/or <20 mm rainfall during driest quarter), and cold stress (>10 days frost year^{-1}, and/or average temperatures <25 °C during the wet season, and/or temperature seasonality >50% higher than in humid tropics). Currently, 72% of plantation area is located in sub-optimal zones where reduced yields are likely and 57% is located in areas where there is a risk of unsustainability (30% face topographic risk, 14% forest risk, 9% typhoon risk and 4% drought risk).

3.3. Conversion of biologically important habitats

The land that has been converted to rubber plantations includes a variety of natural and cultivated lands, much of which were of high-value for biodiversity conservation, landscape functioning and/or food security (Table 3). For instance, between 2005 and 2010 (areas partly overlap):

- almost 2500 km^2 of land was converted to rubber that was previously classed as natural vegetation with tree cover (Bartholomé and Belward, 2005);
- 512 km^2 was converted in internationally important areas for biodiversity conservation (Key Biodiversity Areas; KBAs) and 610 km^2 in protected areas;
- 1624 km^2 of rubber spread into regions that are important for linking key habitats for species of conservation concern (conservation corridors);
- approximately 1370 km^2 of the converted land was previously classified as a mosaic of cropland and natural vegetation (e.g. shifting cultivation) (Bartholomé and Belward, 2005).

These trends demonstrate that protected areas have only a limited capacity to reduce the spread of rubber. Planting rubber on high-biodiversity or ecologically/socio-economically important land has frequently taken place in areas where environmental risks are great enough to threaten the sustainability of plantations: e.g. 61% of the area converted in protected areas, 70% in KBAs, 72% of the area previously under forests, and 84% under shifting cultivation (with the qualifier that the area classified as previously under forest or shifting cultivation is based on global land cover data from 2000 (Bartholomé and Belward, 2005) and there may have been intermediate land conversion in the intervening years).

3.4. Future predictions of rubber spread

Going forward, an ability to predict the future spread of rubber plantations is needed for land use planning. However, rubber plantation spread is challenging to monitor from satellite imagery and/or national statistics. The spectral signature of mature rubber plantations is similar to that of forest, and young rubber can easily be misclassified as other types of cultivation (Li and Fox, 2012). National statistics may be inaccurate due to the frequently unregulated nature of plantation expansion (Xu et al., 2014). Models fitting candidate predictors representative of environmental suitability and infra-structure showed that in all countries distance to the nearest neighbour plantation was the most

Table 1
Recent examples of rubber plantation failures, significant damage and/or significantly lower yield in marginal environments.

Zone	Examples of recent environmental damages to rubber plantations
Typhoon risk zone	Typhoon Haiyan (November 2013) destroyed plantations in Vietnam (International Federation of Red Cross and Red Crescent Societies, 2013). Losses of plantations worth US$ 250 million in Vietnam occurred through typhoons Wutip (September 2013) and Nari (October 2013), affecting 45–55% of plantations in two provinces (Anomynous, 2013a; Tuoitrenews, 2013). Typhoon Damrey caused major plantation damage on Hainan in 2005 (Anomynous, 2005).
Altitudes above 900 m and steep slopes	Rubber plantations >900 m and slopes >24° are not profitable (Yi et al., 2014). Plantations at high altitude and unfavourable aspects in Xishuangbanna, China suffer regular cold damage (c. every 8 years) (Chapman, 1991).
Drought risk zone	A drought in 2010 affecting plantations in N Thailand, Laos, Vietnam and S China resulted in a loss of US$ 26.35 million in Xishuangbanna, China alone due to reduced yields, disease (powdery mildew) and shortages in water for rubber processing (The Rubber Economist, 2010). Tree mortality of up to 22% occurred in Khon Kaen, NE Thailand following a 4-month period of low rainfall in 2010 (Clermont-Dauphin et al., 2013). Significant mortality (up to 50% in young plantations) occurred between Chum Pae and Chayapum, Thailand, following the dry year of 2004 (F. Do, *personal communication*).
Frost risk zone	Sustained low temperatures and frost resulted in major damage in Yunnan Province, China in December 2013 (Anomynous, 2013b). Extreme cold weather in 2009/2010 killed 95% of the Vietnam Rubber Group's rubber in four provinces in N Vietnam (Lộc, 2013). Freezing-hazard in S China in 2008 caused major damage (Shaokai and Nengrui, 2008).
Sup-optimal marginal zones	Thai provinces with <1200 mm annual rainfall had significantly lower yield (c. 300 kg ha^{-1}) than provinces with more rainfall (two-sided permutational t-test from N = 62 provinces in 2011 and 2012: t_{2011} = 3.7678, $P \leq 0.001$; t_{2012} = 3.9819, $P \leq 0.001$). Yield data was obtained from the Department of Agriculture Thailand (2013). Significantly reduced growth rates (60%) were observed in Khon Kaen, NE Thailand due to variable precipitation and critical daily vapour pressure deficits even in the rainy season (Clermont-Dauphin et al., 2013). Reduction in yield by 24% occurred due to drought on Hainan in 2005 (Shaokai and Nengrui, 2008). Cost of investment per ha in NW Vietnam twice as high as in SE Vietnam. Cold weather and hot wind resulted in low growth rate and abnormal development, leading to low productivity and high mortality (Lộc, 2013). Seedling mortality rates of up to 30–40% in the Vietnamese Highlands and N Central Coast occur due to cool temperatures during the rainy season, low levels of sunlight, susceptibility to disease, and a pronounced dry season. Mature rubber development is hampered by regular strong winds, typhoons, fires and floods. Average yields (highlands 1270 kg ha^{-1} and coast 1630 kg ha^{-1}) are well below SE Vietnam (1990 kg ha^{-1}) (Delarue and Noël, 2009; Priyadarshan et al., 2005).

Table 2
Examples of the economic and environmental risks associated with planting rubber.

Planting environment	Examples of risks
Non-Marginal **Humid tropics (=historically suitable):** yields are reliable; long term prospect; e.g. in the south of Thailand.	**Private sector:** Normal enterprise risks (crop failure or loss due to e.g. disease; rubber price crash). **Smallholder:** As above, but tendency towards single income source carries increased risk. **Public:** Declining water quality due to use of agro-chemicals; reduction of public goods such as carbon sequestration (compared to primary forest), biodiversity and non-timber forest products; loss of small markets, (genetic) crop diversity, and traditional agricultural practices; "land grabbing" when land concessions are granted in the face of uncertain land tenure.
Risky Environments **Altitudes above 900 m and steep slopes:** yields are often less than in humid tropics; long-term sustainability unknown; e.g. Xishuangbanna, China.	**Private sector:** Rarely own land at high altitudes. **Smallholder:** In addition to risks in humid tropics rubber farming >900 m and at slopes >24° may be non-profitable even at high price levels. Furthermore, risk of long-term degradation of land due to top-soil erosion, soil compaction, disruption of natural stream flows, stream sedimentation and greater risk of landslides. Potential exposure to risk could be very high where rubber is the sole income source. **Public:** In addition to risks in humid tropics degradation of landscape and ecosystem services due to accelerated erosion, increased risk of land slides, soil compaction, stream sedimentation, declining water quality due to heavy use of agro-chemicals on degraded soils; loss-loss scenarios (e.g. clearance of high-biodiversity value land for short-term returns but with high long-term environmental and socio-economic costs).
Drought risk zone: yields are often less than in humid tropics and there is little or no production during dry season; long-term sustainability unknown; e.g. parts of NE Thailand.	**Private sector:** In addition to risks in humid tropics the rubber price needs to remain sufficiently high to account for potential production shortages during dry season and risk of diseases when plant vigour is reduced. Furthermore, risk of regional water deficits (large quantities of water needed for rubber processing). **Smallholder:** As for private sector (but marginality and potential of long-term land degradation means potential exposure to risk where it is the sole income source). **Public:** In addition to risks in humid tropics risk of degradation of landscape and ecosystem services due to depletion of ground water and negative feedbacks between rubber planting and climate; loss-loss scenarios.
Zones with frequent extreme events (typhoon and frost risk zones): yields are reliable most years but sudden tree loss may occur; long-term sustainability unknown; e.g. Hainan and coastal Vietnam.	**Private sector:** In addition to risks in humid tropics prices need to remain high to make up for potential sudden plantation loss e.g. due to regularly occurring tropical storms or prolonged frost. **Smallholder:** As for private sector extreme events could lead to sudden income loss and lengthy income lags during plantation restoration, which may be catastrophic if limited financial reserves are in place. **Public:** Loss-loss scenarios (e.g. clearance of high-biodiversity value land for a crop that is poorly adapted to high winds and/or frost and that may be abandoned when rubber prices fall).

important predictor (relative predictor contribution 36–59%; Table B.2) for spatial patterns in rubber spread between 2005 and 2010. This suggests that rubber spreads by farmers copying a seemingly lucrative activity from their neighbours, and/or taking advantage of existing rubber farming infrastructure in the vicinity. The recent spread of rubber has been largely uncoupled from environmental conditions: sub-optimal environments and unsustainability risks (i.e. levels 2 and 3) explained only 1–2% of variance at the most. Tests for scale-dependency of these results using high-resolution data for Xishuangbanna confirm these general patterns (Table B.2).

Almost all mainland SE Asian countries intend to increase their rubber plantation area by 2020 (Table B.3). If the current trends continue and countries achieve their targets, a substantial loss of land with high-biodiversity value will occur by 2020 (Table 3). In total, 13,310 km^2 classified as forest (ESA, 2010) and 8952 km^2 of land within KBAs are now under imminent threat (within the upper 95% percentile of conversion probability; Fig. 4). Over half of these areas are in environmentally risky areas where rubber growth may be unsustainable. At the time of writing the conversion trends indicated by the country targets are confirmed (Prachaya, 2015), and in the case of Vietnam even more land has already been converted (Lộc, 2013). The prediction that the conversion will affect socio-economically and ecologically important marginal habitats such as community managed forests in northern Vietnam has also been confirmed (Phuc and Nghi, 2013).

3.5. Likely impacts of climate change

Overall, the effects of climate change are expected to lead to a net exacerbation of environmental marginality for up to 69% of *current* and another 55% of *predicted* rubber plantation area in sub-optimal areas (albeit with considerable uncertainty around these predictions, which compound the uncertainties of modelled land use changes with modelled climate changes). The greatest risks of unsustainability are associated with accelerated erosion due to increased precipitation for high altitude plantations, increased risk of drought, and an elevated risk of storm damage – although uncertainty in projections of precipitation and the intensity and frequency of tropical storms is high (IPCC, 2013). Specifically, there may be increased precipitation in the wettest months for 96–100% of the area currently situated in the topographic risks zone plus 87–100% of the areas for predicted future plantations. These conditions are predicted by most models in all scenarios (Fig. 5). Predictions regarding an increased drought risk in the dry stress zone are more variable across models (Fig. 5). On average, 38–76% of plantations currently under dry stress, plus 48–67% of predicted future plantations, are anticipated to remain dry or experience an increase in the number of 'dry' months (<60 mm precipitation). Overall, there is a projected decrease in soil moisture in almost the entire study area (IPCC, 2013). Furthermore, rubber planted in the zone affected by tropical storms may have an elevated risk of storm damage. More positively, frost risk is expected to decrease (strong agreement between models; Fig. 5).

4. Discussion

Increasing demand, and decreasing rubber production in its core suitability area due to the expansion of oil palm, have created economic incentives for rubber production in marginal environments. The current study shows evidence for a clear-cut shift in the environmental space where rubber is now being planted, beyond that of its natural range and areas in which it was traditionally planted. Although local micro-climatic conditions may ameliorate risks of environmental marginality, and novel environments that differ from the 'historically suitable space' may not be sub-optimal per se for specifically bred clones, there is increasing evidence that the massive scale land conversion to mono-culture rubber in areas well outside of its natural environmental space is having significant negative long-term environmental and social impacts (Tables 1 and 2). Typhoons in 2013, for example, destroyed rubber plantations worth more than

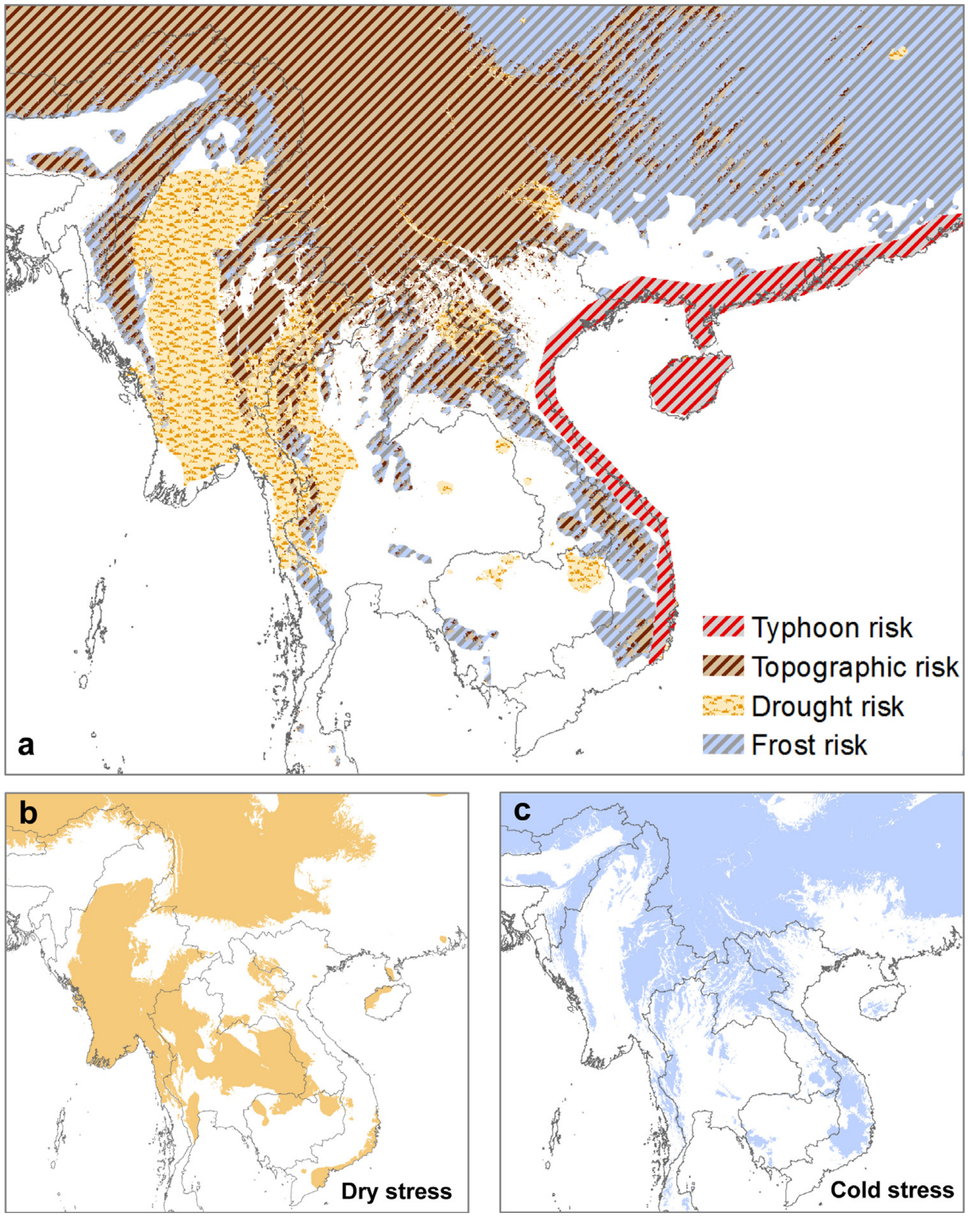

Fig. 3. Environmental stress map. (a) Areas where environmental stresses are so severe that there is a risk of unsustainability. To generate a composite map of primary risks we first delineated the typhoon and topographic risk zones, and then assigned remaining risk areas to the drought zone or frost zone depending on which was furthest from its optimum (median value within the natural rubber range). (b) Sub-optimal areas with dry stress. (c) Sub-optimal areas with cold stress.

US$ 250 million in Vietnam alone. Moderate windspeeds of >3 m s^{-1} can severely inhibit tree growth and the flow of latex, and the branches and trunks of rubber trees snap when exposed to high winds (from c. 17 m s^{-1}; Priyadarshan, 2011), making them more susceptible to storm damage than many other cash crops. Restoration or recovery from such extreme damages (extending 3–7 years) means lengthy income lags. A recent example of the adverse effects of water stress on the economic viability of rubber occurred during the 2010 drought in northern Thailand, Laos, Vietnam and southern China. A loss of US$ 26.35 million occurred in Xishuangbanna alone due to yield decreases, infection of trees with powdery mildew (*Oidium heveae*) and shortages in the large quantities of water needed for rubber processing. Cold damage and loss of rubber trees are regularly reported from marginal areas, and planting at altitudes >900 m or on steep slopes is often not profitable even when market prices are high (Table 1). Our analysis suggests that these problems will increase in the future as predicted climate change is likely to lead to a net exacerbation of environmental marginality for both current and future projected plantation area (Fig. 5).

Going beyond the crop itself, there is evidence that establishing rubber plantations on marginal lands may lead to wider ecosystem problems. For example, plantations on steep hillsides and/or easily erodible soils causes accelerated top soil erosion and stream sedimentation (Ziegler et al., 2009). The establishment of terraces on steep slopes represents drastic alterations to the physical soil surface that may disrupt natural hydrological flow pathways and contribute to accelerated erosion (Li et al., 2012). The increased need for the use of agro-chemicals on such degraded soils may reduce surface and subsurface water quality (Ziegler et al., 2009). Rubber has also been linked to stream desiccation and potential regional water deficits in areas with a pronounced dry season due to its higher evaporative demand compared to most traditional

Table 3
Past and predicted conversion of biodiversity-rich and/or ecologically important habitat to rubber plantations by country. PA, protected area; KBA, Key Biodiversity Area; Cons. cor, conservation corridor. Predicted losses by 2020 assume that the current spatial patterns of land conversion remain constant, that a total area of 18,600 km^2 will be converted (country rubber development targets), and that cells with the highest modelled probability of future conversion are targeted first.

	Conversion of biodiversity-rich and/or ecologically important habitat 2005–2010				Predicted losses by 2020 based on country expansion targets (figures partly overlap)				
	PA (%)	KBA (%)	Forest (%)[a]	Natural vegetation with tree cover (%)[a]	PA (km^2)	Cons. cor. (km^2)	KBA (km^2)	Forest (km^2)[a]	Natural vegetation with tree cover (km^2)[a]
Cambodia	40	27	33	46	2638	2546	1732	1491	2186
China	11	9	10	57	–	–	–	–	–
Laos	5	10	12	29	84	559	149	88	366
Myanmar[b]	1	8	17	24	3	67	149	269	432
Thailand[b]	20	7	12	13	1756	1836	564	1370	1422
Vietnam[b]	31	17	20	26	1900	2773	628	994	1364
Total (km^2) (% in potential risk areas)					6381 (37%)	7781 (43%)	3222 (47%)	4212 (44%)	5770 (43%)

[a] These figures are approximate due to uncertainties in the global land cover data (potential classification errors, and the classification is from 2000 – there may have been intermediate land conversion steps in the intervening years).
[b] S Thailand, SW Vietnam and W Myanmar are not included in the study area. The prediction figures assume that rubber is being planted within the study area.

types of vegetation (Guardiola-Claramonte et al., 2010, 2008; Ziegler et al., 2009). The conversion of forest to rubber may also negatively impact the regional climate (Xu et al., 2014).

Clones produced from breeding programmes have increased the environmental tolerances of rubber but evidence to-date suggests that these gains are not sufficient to ensure sustainable cultivation in the range of environments that the crop is being planted into. For instance, the majority of the material planted in China (GT1 and RRIM600) has been considered relatively tolerant to chilling and drought. However, there have been large-scale plantation failures in southern China due to drought and cold temperatures in 2008, 2010 and 2013. With these failures in mind, it is worth noting that these clones were bred in areas (e.g. GT1 in East Java) that are climatically much closer to the native rubber environmental space than the extreme marginal environments that rubber is now being planted into. Going forward, a greater understanding of which clones are being planted where, and their respective success and failure rates, will serve to refine our

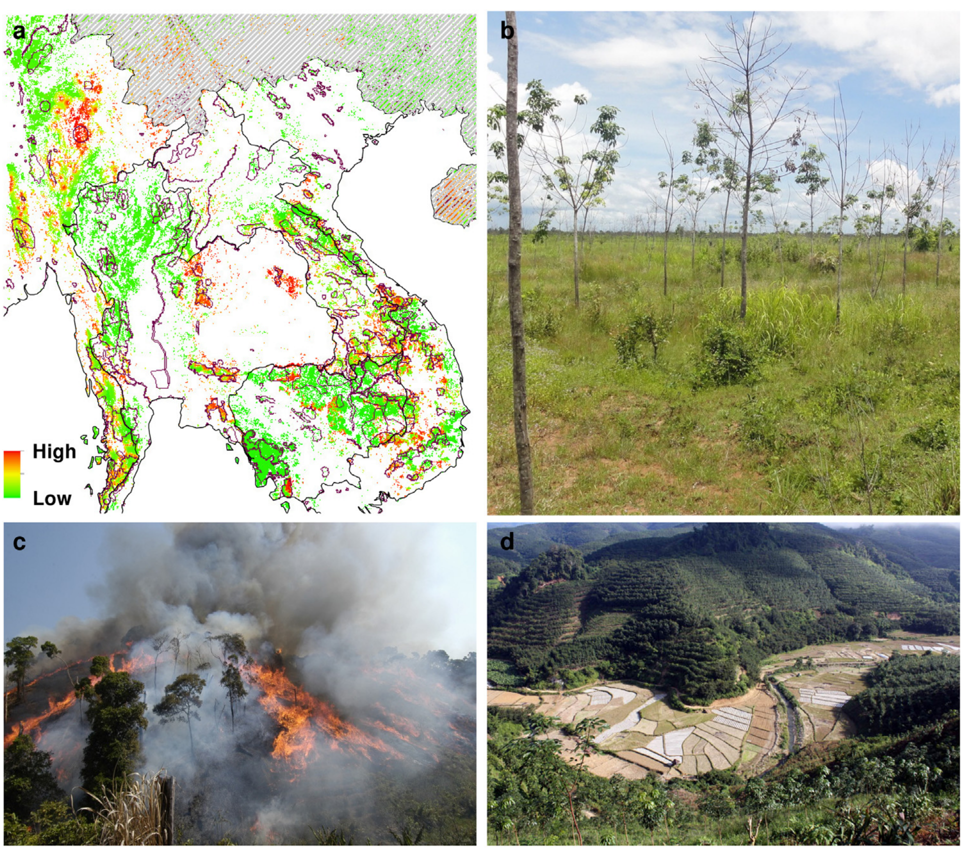

Fig. 4. Predicted conversion risks. (a) Predicted conversion risk to the remaining forests and Key Biodiversity Areas (KBAs). The KBAs are shown as purple polygons. China is greyed out as no further rubber expansion targets are known for this country. (b) Failed rubber plantation in southern Laos near the Cambodian border. (c and d) Rubber plantations are rapidly displacing forests and shifting agriculture in Xishuangbanna, China. Twenty percent of the landscape in this prefecture has been converted to rubber plantations – partly on steep slopes and altitudes >900 m.

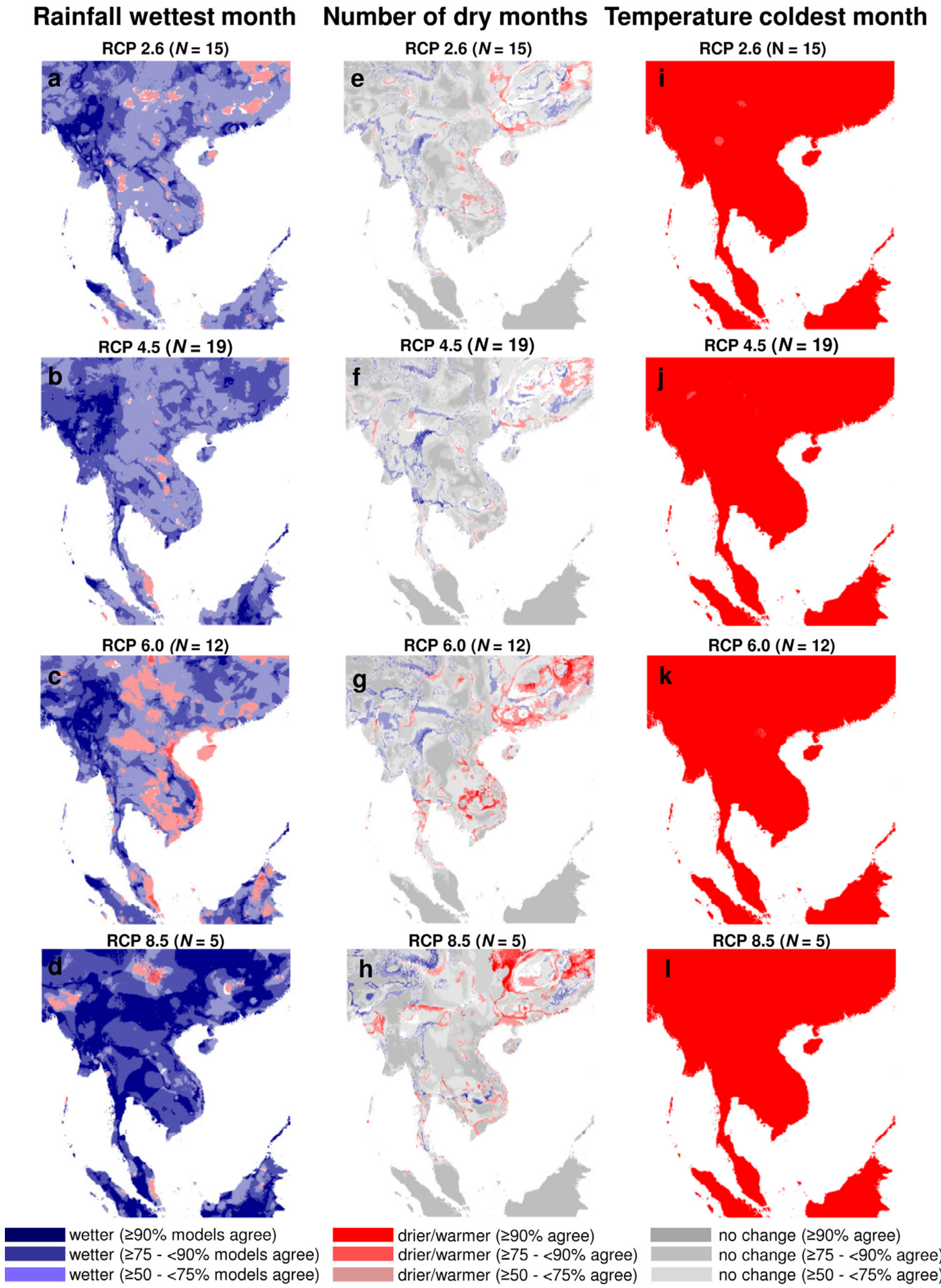

Fig. 5. Direction of climate change and model agreement across four Representative Concentration Pathways (RCPs) by 2050. The number of models included in the analysis is shown in brackets (*N*). Panels i–l show little variation as almost all models unanimously agree that temperatures in the coldest month will increase throughout the study area under all RCPs.

understanding of risk based on current genetic resources. Increasingly hardy clones from ongoing breeding programmes may then serve to further ameliorate risks of plantation failure.

One major problem that remains is that despite risks of plantation failure in marginal environments, as long as rubber is more lucrative than any other type of crop in the short term, this will inevitably drive land use change. Expansion is also promoted by various national government policies aiming to move traditional shifting agriculture to more intensive agricultural systems. Carefully formulated payment for ecosystem services, such as the UN Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+), which consider the value of natural forests beyond carbon, may have the potential to reduce natural forest conversion to rubber plantations for short term gains. However, when rubber prices are high, payments to offset the opportunity costs for avoided land conversion would have to be significant. Certification schemes for "environmentally friendly" rubber (produced for example in rubber agroforests) may also have an ameliorating effect; however the returns of such schemes may be slow as they require market development and policy shifts. These market/incentive-driven strategies will need to be combined with a more immediate awareness raising programme of the economic and environmental risks of the conversion of marginal lands to promote sustainable income streams and avoid potentially irreversible environmental degradation.

5. Conclusions

Our findings show that rubber is increasingly planted into marginal environments where there is a risk of unsustainability. Given this trend there is an urgent need for systematic and region-wide monitoring to quantify plantation losses and impacts on ecosystem services caused by the expansion into marginal environments to underpin the formulation of appropriate policy interventions that limit environmental and societal impacts. Although rubber at current price levels produces lucrative yields in many marginal areas and there is frequently a lack of better alternative crops, policy interventions and greater awareness are needed given that rubber prices are volatile and cash crops such as rubber are currently the main drivers of forest loss in continental SE Asia. Our analysis highlight a clear potential for loss-loss scenarios, such as the clearing of high-biodiversity value land for a crop that is poorly adapted to local conditions and, by altering landscape function whilst not producing long-term sustainable yields, may ultimately also compromise livelihoods.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2015.06.002.

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