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The potential for REDD+ to reduce forest degradation in Vietnam

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Abstract

Natural forests in Vietnam have experienced rapid declines in the last 70 years, as a result of degradation from logging and conversion of natural forests to timber and rubber plantations. Degradation of natural forests leads to loss of biodiversity and ecosystem services, impacting the livelihoods of surrounding communities. Efforts to address ongoing loss of natural forests, through mechanisms such as Reduced Emissions from Deforestation and Degradation (REDD+), require an understanding of the links between forest degradation and the livelihoods of local communities, which have rarely been studied in Vietnam. We combined information from livelihood surveys, remote sensing and forest inventories around a protected natural forest area in North Central Vietnam. For forest-adjacent communities, we found natural forests contributed an average of 28% of total household income with plantation forests contributing an additional 15%. Although officially prohibited, logging contributed more than half of the total income derived from natural forests. Analysis of Landsat images over the period 1990 to 2014 combined with forest inventory data, demonstrates selective logging was leading to ongoing degradation of natural forests resulting in loss of 3.3±0.8 Mg biomass ha^{-1} yr^{-1} across the protected area. This is equivalent to 1.5% yr^{-1} of total forest biomass, with rates as high as 3% yr^{-1} in degraded and easily accessible parts of the protected area. We estimate that preventing illegal logging would incur local opportunity costs of USD $4.10±0.90 per Mg CO_2, similar to previous estimates for tropical forest protected areas and substantially less than the opportunity costs in timber or agricultural concessions. Our analysis suggests activities to reduce forest degradation in protected areas are likely to be financially viable through Vietnam's REDD+ program.

1. Introduction

Deforestation and forest degradation are occurring across the tropics (Hansen et al., 2013; Sodhi et al., 2010), resulting in emissions of carbon dioxide (Le Quere et al., 2018), changes to local climate (Baker and Spracklen, 2019), loss of biodiversity (Barlow et al., 2016) and other ecosystem services, and impacts on the livelihoods of local people (Sodhi et al., 2009). REDD+ (Reduced Emissions from Deforestation and Degradation) represents a collection of actions aimed at reducing carbon dioxide (CO_2) emissions associated with deforestation and forest degradation and increasing forest carbon stocks through improved forest management (Corbere & Schroeder, 2011). Developing REDD+ activities that both protect forest resources and the livelihoods of local people (Duchelle et al., 2017) requires an understanding of how the livelihoods of local communities both depend on and impact forest resources.

Our study focuses on Vietnam, where natural forests have experienced widespread degradation and loss over the last few decades. Forest cover in Vietnam declined from 43% in 1943 to a minimum of 16-27% in 1993, before increasing to 41% in 2016 (Meyfroidt & Lambin, 2008, 2009; Cochard et al., 2017). Increased forest cover has resulted largely from expansion of plantation forests and has occurred alongside continued degradation of natural forests (Khuc et al., 2018). In Vietnam, as in the rest of Southeast Asia, logging is the main driver of forest degradation (Hosonuma et al., 2012). In an attempt to prevent degradation of natural forests, Vietnam has implemented successive policies to reduce logging in natural forests (Meyfroidt & Lambin, 2009; Sikor & To, 2011). However, the reduction of timber extraction quotas has exacerbated illegal logging (Sunderlin, 2006). In 2009, Vietnam was identified as a pilot country under the UN-REDD Programme and subsequently received support through the World Bank Forest Carbon Partnership Facility (FCPF) (UNDP, 2009; Brockhaus & Di Gregorio, 2014). Today, Vietnam is a UN-REDD Programme Partner Country, with a National REDD+ Action Plan that runs until 2030 and actively supports numerous local projects (Hoang et al., 2019).

Efforts to reduce forest degradation through increased enforcement and reductions in illegal logging have potential social costs for local communities (Brockington et al., 2006). People living in and around forests use forest resources for subsistence and cash income as well as benefiting from other ecosystem services provided by the forest (Sunderlin et al., 2005; Vedeld et al., 2007; Angelsen et al., 2014; Sodhi et al., 2009). Through supporting sustainable use of forest resources, REDD+ may incur an opportunity cost on forest users associated with restrictions on the use of forest resources (Ickowitz et al., 2017; Duchelle et al., 2017).

Our study focuses on the relationship between use of forest resources by local communities and forest degradation which has rarely been studied in Vietnam (Sunderlin & Ba, 2005; McElwee, 2008; 2010). Our objective was to assess the contribution of forests to local livelihoods and the impact of this resource use on natural forests, specifically biomass storage. We collected information from community interviews, forest inventories and satellite remote sensing. Through combining this information we estimated the opportunity costs on local communities associated with efforts to reduce forest degradation. Our aim was to contribute new understanding of the potential for REDD+ to reduce forest degradation and support local livelihoods in forested landscapes of Vietnam.

2. Methods

2.1 Study Area

Our study area is the Khe Nuoc Trong (KNT) watershed protection forest (17.0°N, 106.6°E) and surrounding communities in Quang Binh Province (Figure 1), part of the North Central Coast (NCC) region. In 2015, average forest cover in the NCC region was 57%, comprising 74% natural forest and 26% forest plantation (MARD, 2018). Natural forest in the NCC region is heavily degraded, with 62% of the natural forest classified under national standards as poor quality (<100 m^3 standing timber), 21% as medium quality (200 – 300 m^3) and only 10% as rich quality (>300 m^3) (MARD, 2018). The NCC region is developing an Emissions Reduction Program for the FCPF Carbon Fund (MARD, 2018).

The Khe Nuoc Trong (KNT) watershed protection forest (16.9°N-17.05°N, 106.5°E-106.8°E) was established in 2008. It includes lowland and mid-montane evergreen forest with elevations ranging from 120 m to 1220 m and has a current area of around 23 000 ha. KNT is managed by the state for the protection of ecosystem services, predominantly for the protection of water resources. Logging and hunting are not permitted and no government licensed logging has occurred since 2008. Informal logging by local communities is ongoing and considered illegal but enforcement is often limited. Prior to 2008, logging by the state and local communities occurred, but records of timber extraction are not available. Compared to the wider NCC region, KNT has higher quality forests, consisting of 46% rich forests, 22% medium forests and 31% poor forests. KNT experiences a tropical monsoon climate with the coolest months in December and January and the warmest in July and an average temperature of 22°C. Annual rainfall is 2080 mm with the driest months in February to April (minimum of 20 mm $month^{-1}$) and the wettest in October (450 mm $month^{-1}$).

2.2 Livelihood surveys

KNT is surrounded by 5 communes, administrative zones similar to county level. Villages within three communes (Kim Thuy, Vinh O and Vinh Ha) have easy access to the forests in KNT. These communes cover an area of 73 472 ha with a population of 7251 in 30 villages with a total of 1968 households, mostly from the Van Kieu ethnic minority group (Table 1). Levels of poverty in the NCC region are some of the highest in Vietnam (MARD, 2018), with annual household income of USD \$1500 to \$2000 in these communes.

We conducted surveys in Kim Thuy Commune in July 2016 and Vinh O and Vinh Ha communes in March 2018. In each commune, meetings with commune leaders were used to share research objectives and to identify villages where households have reasonable access to and used natural resources within KNT. Identified villages are kept anonymous but were typically close (< 3 km) to the border of KNT. Focus groups discussions with 8-10 participants were conducted within each village, to better understand the practical livelihood issues of the villages and to inform questionnaire design. In each identified village, structured household questionnaires (see Supplementary Material) were then conducted with the head of the household in randomly selected households. In total, 300 households interviews were conducted (140 in Kim Thuy, 80 in Vinh O, 80 in Vinh Ha), representing 10-25% of the households in each commune (Table 1). The main objective of the interviews was to assess the different income sources for each household, based on the methods in Anglesen et al. (2014). For each household, income from all sources was recorded including crop production, animal husbandry and animal products, forest-based activities (plantation and natural forests), wage labour, and government support. Households were also asked about the perceived change in forest quality. Field surveys were concluded with commune-level stakeholder meetings.

2.3 Remote sensing

We analysed Landsat satellite images to identify forest disturbances as described in Stas et al. (2020). The Earth Explorer and the USGS ESPA ordering system were used to retrieve all available Landsat images for Path/Row 126/48 and 125/48 with less than 70% cloud cover between 1990 and 2014 inclusive. This period is chosen to allow us to understand whether the change in protection status of the forest area in 2008 had any impact on forest loss. The pixel_qa layer supplied with each Landsat image was used to remove cloud and cloud-shadow covered pixels. A total of 401 Landsat 4/5, 227 Landsat 7 and 24 Landsat 8 surface reflectance images were obtained, providing an average of 16 images per year. Gaps in Landsat 7 images due to the Scan Line Corrector failure were treated as missing data, in a similar way to pixels obscured by clouds.

We identified forest disturbances using the Normalized Burn Ratio (NBR) that has been widely used to detect forest cover change (Li et al., 2017) and forest disturbance through selective logging (Grogan et al., 2015; White et al., 2017; Langner et al., 2018; Lima et al., 2019), wildfire (White et al., 2017) and insect damage (Meigs et al., 2011; Senf et al., 2015). NBR is particularly suited to identifying forest disturbance due to the sensitivity to bare soil, non-photosynthetic vegetation, and vegetation structure and the lower contamination from atmospheric haze (Grogan et al., 2015; Langner et al., 2018; White et al., 2017). We calculated NBR as:

$$NBR = \frac{NIR - SWIR}{NIR + SWIR}$$

where SWIR is the shortwave Infrared band and NIR is the near-IR band. We used the Landsat images to create a time series of NBR for each pixel. We then identified disturbance as pixels with long-term mean NBR > 0.5 and exhibiting a temporary reduction in NBR, with two or more consecutive values of NBR < 0.5, allowing us to distinguish between recently disturbed canopy cover and naturally open canopy (Langner et al., 2018). We calculated the annual rate of disturbance between 1990 and 2014 as the number of pixels with an identified disturbance in each year.

2.4 Forest surveys

Forest biomass stocks and biomass removal from logging within KNT were estimated from forest surveys conducted between April 2016 and June 2017. We established 24 permanent plots (0.25 ha, 50 m × 50 m) within KNT (Fig. 2) across rich, medium and poor forest classes. Establishment of plots and methods to calculate biomass storage are fully detailed in Stas et al. (2020) and described briefly here.

In each plot, all living stems ≥10 cm diameter at breast height (DBH) were measured. All living stems ≥5 cm DBH were measured in a belt transect of 4 × 50 m. Living above-ground biomass (AGB) was computed using an allometric equation including DBH, tree height and wood density (Réjou-Méchain et al., 2017). Above-ground necromass for fallen and standing dead wood was also calculated. AGB was calculated as the sum of living biomass in stems ≥5 cm DBH and necromass. Below ground biomass (BGB) was estimated as 24% of AGB where AGB ≥ 125 Mg ha^{-1}, else 20%. Total biomass (B, Mg ha^{-1}) was the sum of AGB and BGB. Soil organic carbon was not included here, as this does not change significantly during forest degradation (Stas et al., 2020).

To assess the amount of biomass extracted by logging, the number and diameter of logged tree stumps ≥10 cm DBH within each plot were counted. We assume that trees ≥ 10 cm DBH will largely be logged for timber, rather than firewood. The total amount of biomass removed by logging (L, Mg ha^{-1}) was estimated based on the ratio of basal area of the logged stumps (A_1) to remaining basal area of the plot (A_2), multiplied by total biomass:

$$L = (A_1 / A_2) \times B$$

Wood decay means that the logged stumps will disappear over time, and the logged stumps identified in our plots will represent logging activities over a certain time period. To estimate this time period, we assumed a wood decay rate (k) of 0.18±0.02 yr^{-1} (Baker et al., 2007). The rate of removal of biomass through logging (R, Mg ha^{-1} yr^{-1}) was estimated as:

$$R = L \times k$$

The average biomass removal from logging in rich, medium and poor forests was estimated as the average across the plots in each category. The total biomass removal from logging (Mg yr^{-1}) was calculated as the average rate of removal multiplied by the area (A; ha) of that category:

$$T = R \times A$$

Our biomass removal estimate only include trees that have been clearly logged and does not account for additional trees damaged during logging operations. We may therefore underestimate the reduction in biomass due to selective logging.

2.5 Opportunity costs of logging and costs of REDD+ projects

206 We combined information from the forest and household surveys to estimate the amount of biomass removed and income received per unit of biomass removed at the household level. We estimated the average local opportunity cost (O, \$ per tCO_2) of preventing logging as the average income local households derived from illegal logging (I; \$ $household^{-1}$ yr^{-1}) divided by the estimated average annual biomass wood extraction per household (W; tCO_2 $household^{-1}$ yr^{-1}):

211 $$O = I / W$$

212 W was calculated as the total annual biomass extraction from within KNT (T; Mg biomass yr^{-1}) estimated from the forest surveys converted to mass of CO_2 (to convert biomass to carbon we multiplied by 0.47), divided by the total number of households in the three communes (n):

215 $$W = (T \times 0.47 \times 3.67) / n$$

216

217 To explore the potential for REDD+ finance to reduce forest degradation in Vietnam we estimated the costs associated with establishing a REDD+ project. In addition to the opportunity cost, the breakeven carbon price (P, \$ per tCO_2) also includes an implementation cost (I, \$ per tCO_2) and the set-up cost (S, \$ per tCO_2):

221 $$P = O + I + S$$

222 We estimated project setup and implementation costs using average setup (\$4.95 ha^{-1}) and implementation (\$11.28 ha^{-1} yr^{-1}) costs reported from a REDD+ project in Cambodia (Warren-Thomas et al., 2018). We acknowledge that costs in our project, which is in a different country and ecosystem, are likely to be different. To convert these values to costs per tCO_2, we scaled by the area of KNT and total emission reductions that would be achieved if all poor and medium forests within KNT were restored to rich forests assuming a 30 year project timeframe.

228

229 3. Results and discussion

230 3.1 Household livelihoods

Figure 3 shows the use of natural forest resources reported in household questionnaires. Firewood was the most frequently used resource, used by 82% of households. Each of the other resources was used by approximately half of households, with 44% collecting timber, 50% collecting honey, 54% hunting and 54% collecting other non-timber forest products (NTFPs).

Resources from natural forests accounted for 28% of total household income, greater than the contribution from animal breeding (22%), crop cultivation (10%), or plantation forestry (15%) (Fig. 4). The different communes exhibit different contributions from the different sectors, with natural forests contributing 12-42% and plantation forestry contributing 9-28%. At another location in Vietnam, natural forests accounted for 14% and plantation forests 5% of total income (McElwee, 2008). In our study, forests (natural and plantation) account for 42% of total household income, greater than the pan-tropical mean of 22% (Angelsen et al., 2014) reported from a large meta-analysis.

We found the largest contributions to overall income came from logging in the natural forest (16%; USD $277 / household / year), acacia plantations (15%), animal husbandry (14%) and salary and social allowances (12%) (Fig. 5). There was variability in this distribution across the different communes (Supplementary Fig. 1), with logging in the natural forests (6-22%) and acacia plantations (9-28%) consistently contributing a substantial fraction of total income. Income from plantation forests was greater than the pan-tropical mean of 1% (Angelsen et al., 2014), despite the relatively small area of plantation available to each household in our study (0.7-1.5 ha per household) (Table 1).

In our study, logging was the most important natural forest resource contributing 58% of the income from natural forests (Fig. 6). Honey (10%) and other NTFPs (18%) also make important contributions. Hunting makes a smaller contribution (6%), but is still greater than reported elsewhere in Vietnam (McElwee, 2010). Meta-analysis of previous studies also report ecosystem services are

256 dominated by woodfuel and wood products (timber, building poles) which accounted for 60% of
257 forest income (Angelsen et al., 2014).

258

259 **3.2 Forest degradation**

260 Forest disturbances were concentrated in poor and medium forests in eastern regions of KNT (Fig. 2).
261 The spatial distribution of disturbance identified by our remote sensing analysis was in broad
262 agreement with the distribution identified through focus group discussions and participatory mapping
263 (Stas et al., 2020). Large blocks of disturbance, mostly outside KNT, are associated with acacia
264 plantations. Figure 7 shows the rate of forest disturbance within KNT identified by the remote sensing
265 analysis over 1990 to 2014, during which logging regulations changed substantially. Disturbance rates
266 in specific years can be biased by variability in cloud cover altering availability of cloud free images,
267 so we calculate and report average rates of disturbance over multi-annual periods. Some small areas
268 of acacia plantation occur within KNT, and we exclude disturbances identified within these areas
269 from our analysis. During the 1990s and 2000s, Vietnam reduced harvesting quotas in natural forests
270 and implemented a series of logging bans (Tuynh & Phuong, 2001; Meyfroidt and Lambin, 2009). In
271 2008, KNT was established as a watershed protection forest. However, our analysis shows no
272 evidence of reduced disturbance within KNT, with the average rate of disturbance during the 7 years
273 after reserve establishment (2008-2014, 142.6 pixels yr^{-1}) being greater than the 7 years before
274 establishment (2001-2007; 100.6 pixels yr^{-1}). Ongoing forest disturbance is confirmed by household
275 interviews with 49-64% of households indicating that forest quality had declined in recent years
276 (Table 2). Together this analysis suggests that protected area status that was granted in 2008 and
277 successive nationwide controls on logging have not reduced the extent of logging within KNT.

278

279 Total biomass storage (defined here as AGB for living stems with DBH ≥ 5 cm, root biomass,
280 standing dead wood and woody debris) was greatest in rich forests which stored 284 Mg ha^{-1}
281 compared to 188 Mg ha^{-1} in medium forests and 140 Mg ha^{-1} in poor forests (Table 3). AGB in KNT
282 (229 Mg ha^{-1} in rich, 152 Mg ha^{-1} in medium, and 115 Mg ha^{-1} in poor forests) are similar to other

natural forests in Vietnam (Fig. 8) (Con et al., 2013; Do et al., 2019) with a clear reduction along the disturbance gradient (Hai et al., 2015; Luong et al., 2015; Nam et al., 2018; Stas et al., 2020, MARD, 2018). Allometric equations for both above- and below-ground biomass have been developed specifically for evergreen broadleaf forests in Vietnam (Huy et al., 2016a,b; Kralicek et al., 2017; Nam et al., 2016) and can improve biomass estimates.

We estimated selective logging resulted in an average biomass removal rate of 3.1 Mg ha^{-1} yr^{-1} (Table 3), equivalent to 1.5% yr^{-1} of forest biomass. Greater biomass removal in poor (4.3±1.5 Mg ha^{-1} yr^{-1}, 3.1% yr^{-1}) and medium (6.3±2.3 Mg ha^{-1} yr^{-1}, 3.3% yr^{-1}) compared to rich (1.1±0.7 Mg ha^{-1} yr^{-1}, 0.4% yr^{-1}) forests matches the remote sensing analysis (Stas et al., 2020). We scaled up the estimates from the forest plots to estimate of the total biomass removal through selective logging in KNT of 72800 ±14000 Mg yr^{-1} (Table 3).

Our estimates of biomass removal focused on logging for timber, so we only assessed removal of stems with DBH ≥10 cm. Collection of firewood was common in the villages surveyed, but is likely to be composed of small, dead branches collected close to the villages (McElwee, 2010; Kim et al., 2017). Previous estimates of firewood use in Vietnam are 3.3-13.1 kg $household^{-1}$ day^{-1} (Kim et al., 2017; Techato & Techato, 2018), equivalent to 1.2-4.8 Mg $household^{-1}$ yr^{-1}. If there are similar levels of use in our area, biomass for firewood would represent 4-13% of biomass removal due to logging.

3.3 Forest degradation, livelihoods and the role of REDD+

Through combining information from household interviews and forest inventories we estimate the opportunity costs associated with restrictions on logging. We estimate each household removes 36.4 Mg biomass $household^{-1}$ yr^{-1} (62.7 tCO_2 $household^{-1}$ yr^{-1}) with an opportunity cost of (USD $4.10±0.90 per tCO_2. Our estimated opportunity cost is within the range of previous estimates for

REDD+ projects in protected areas in Southeast Asia (\$3.65-\$10.70 per tCO_2) and substantially lower than in timber or oil palm concession areas in Southeast Asia (\$4.89 - \$55.23 per tCO_2) (Figure 9; Table 4).

We assessed the opportunity costs at the household level. Sikor and To (2011) studied the illegal timber supply chain in northern Vietnam and estimated that one third of income from illegal logging went to villagers and woodcutters, with the remainder going further up the supply chain, including traders, wholesalers, government officials and lawmakers. Therefore the overall opportunity costs of preventing illegal logging may be considerably greater when accounting for the full supply chain. If the division of income is similar to that estimated by Sikor and To (2011), overall opportunity costs of preventing illegal logging would be \$12.30 per tCO_2. The lower opportunity costs estimated for protected areas may partly be a reflection of local opportunity costs of illegal logging not fully accounting for the full supply chain.

We estimated a project implementation cost of \$2.83 per tCO_2 and a setup cost of \$0.04 per tCO_2 (see Methods), giving an overall break-even cost of \$6.97 per tCO_2. Our work therefore suggests that the prices currently paid on carbon markets (\$5-\$13 per tCO_2) are of similar magnitude to the break even costs of a REDD+ project in this region of Vietnam. This suggests that the current price of carbon may be sufficient to support establishment of REDD+ projects in protected areas in Vietnam. There is household variability (Andersson et al., 2018) that is not represented in the averages presented here. For example richer households may have access to more forest plantations (Sikor & Baggio, 2014) making them less reliant on natural forest resources. On the other hand, richer households may have greater access to the tools and resources required for logging, allowing greater exploitation of natural forests. Other studies in Vietnam suggest that forest communities are willing to participate in forest protection schemes where they are paid to cease logging (Nielson et al., 2018) provided that the mechanisms to provide payment are accountable and that distribution is equitable - where households who experience the greater opportunity costs are recompensed accordingly (Pham et al., 2014).

Understanding the contribution of illegal logging to both livelihoods and forest degradation is challenging: records of the incidences of logging are not available and there are sensitivities asking households about illegal activities. We recognise that there will be substantial household-level variation in the contribution of logging to household incomes that are not accounted for in the commune average values we report here. On the ground surveys of the incidences of illegal logging are now required to better ground-truth the remote sensed datasets of forest degradation. Data from Sentinel-2 (Lima et al., 2018), available from 2015, provide better spatial and temporal resolution that will improve ability to identify selective logging particularly in regions with frequent cloud cover.

Our work has demonstrated the large contribution of illegal logging to the livelihoods of local communities combined with the contribution of this logging to forest degradation. REDD+ projects have the challenge of identifying effective interventions that can together reduce forest degradation, whilst maintaining and improving livelihoods. Previous work has suggested that options for better forest management in Vietnam include increased community control and management of forests (Sunderlin, 2006), improved land tenure (Sunderlin et al., 2013; Traedal & Vedeld, 2017), performance-based contracts for the provision of forest ecosystem services (Sikor & Tan, 2011), strengthened forest protection and management of illegal logging (Nguyen et al., 2016). Enforcement of logging regulations in KNT appears to be limited and will need to be strengthened to reduce forest degradation. In recent years, devolution of forest management has increased management of forests by local communities in Vietnam (Sunderlin, 2006; Lambini & Nguyen, 2013). Vietnam has implemented a pilot benefit sharing mechanism, a legal framework for sharing the benefits, rights and responsibilities of forest conservation and management with local communities (Bayrak et al., 2014). In Bach Ma National Park, Vietnam, this scheme increased average household income by 30% through regulated access to NTFP (Huynh et al., 2016). In our study area, forest protection contracts contributed only 2.6% of total household income, insufficient to replace income from illegal logging. Extending the scheme to cover more forest and more households might increase income and reduce the need for illegal logging. Acacia plantations are an important income source for local communities, but timber cycles are too short (3-5 year rotations) to provide the large dimension timber that would reduce pressure on natural forests. Extending rotation period of forest plantations could provide a better source of timber, reduce pressure on natural forests and enhance incomes. However, short rotations are selected by households for a range of practical reasons and delivering extended rotations is likely to be challenging. Protected areas exhibit variable success both at reducing deforestation (Jenkins and Joppa, 2009; Spracklen et al., 2015) and improving livelihoods of local communities (Clements et al., 2014). Protected areas that consider the needs of local communities (Elliot et al, 2001) are also more likely to deliver positive conservation outcomes (Oldekop et al., 2016). Improved dialogue between the protected area management and local communities is required.

Conclusions

We combined information from household surveys, forest inventories and remote sensing to understand the interactions between livelihoods, forest resource use and forest degradation around a protected natural forest in Vietnam. We found that natural forests and plantations together provide 42% of total household income, substantially more than the average of 22% reported across the tropics (Angelsen et al., 2014). We found natural forests were particularly important, contributing 28% of total household income, equal or greater than the income from plantation forests.

Remote sensing analysis and forests surveys demonstrated pervasive selective logging across the protected area. Rates of disturbance remained stable over the period 1990 to 2014, despite the area gaining protected status in 2008. We estimated that illegal logging removed 3 Mg biomass ha^{-1} yr^{-1}, sufficient to progressively degrade the forest. Poor and medium quality forests contained only 50% of the above-ground biomass of rich forests.

Illegal logging made the single most important contribution to local livelihoods, contributing 58% of the total income from natural forests. We estimated opportunity costs for preventing illegal logging as USD $4.10 per tCO_2, similar to opportunity costs in other protected forest areas in Southeast Asia and substantially less than the opportunity costs in commercial timber and plantation concessions. This suggests that activities to reduce unsustainable logging in protected areas in Vietnam may be viable under planned REDD+ programs. A landscape-scale approach to forest management, with improved enforcement within protected areas combined with provision of alternative livelihood strategies to mitigate loss of income from illegal logging, may help reduce further degradation of natural forest areas without harming livelihoods of local people.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Figures

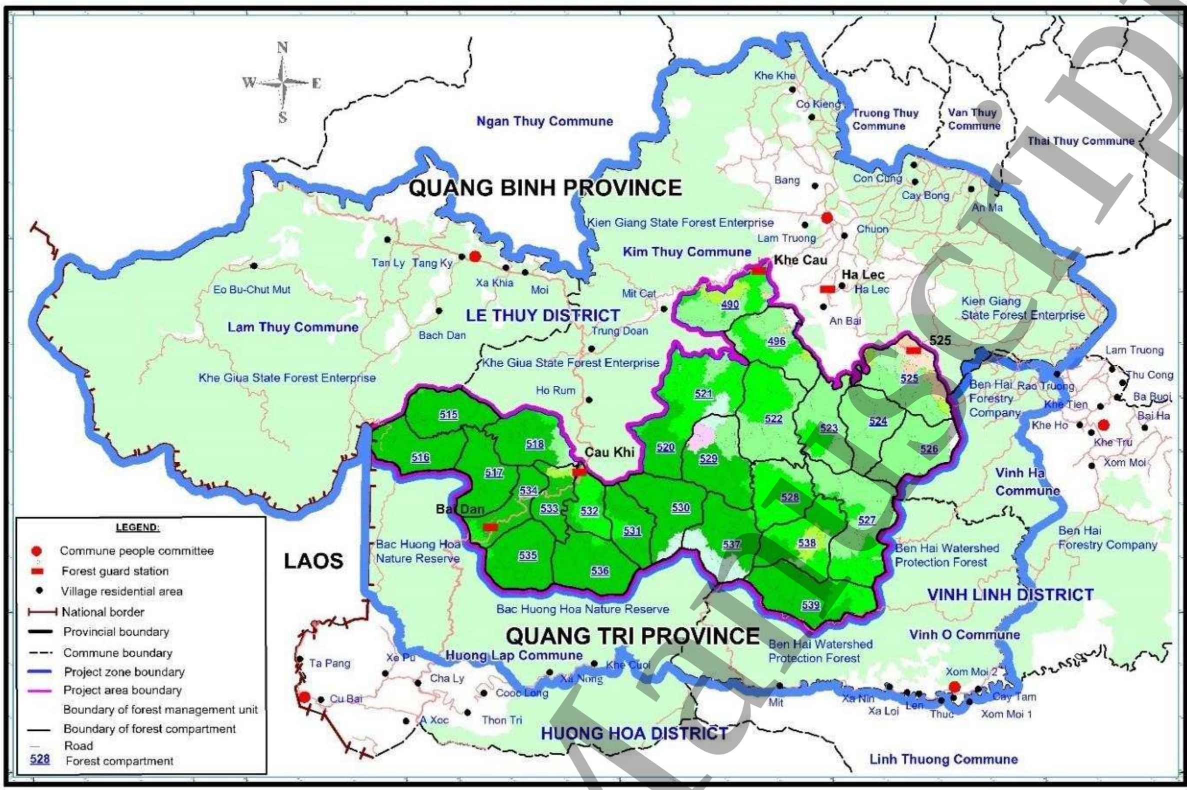

Figure 1. Project area in North Central Vietnam. The Khe Nuoc Trong watershed protection forest is highlighted in green with shading representing forest quality (rich: dark green, medium: bright green, poor: light green). Surrounding communes (Kim Thuy, Vinh Ha and Vinh O) where surveys were completed are shown within the blue line. Villages are marked with black circles.

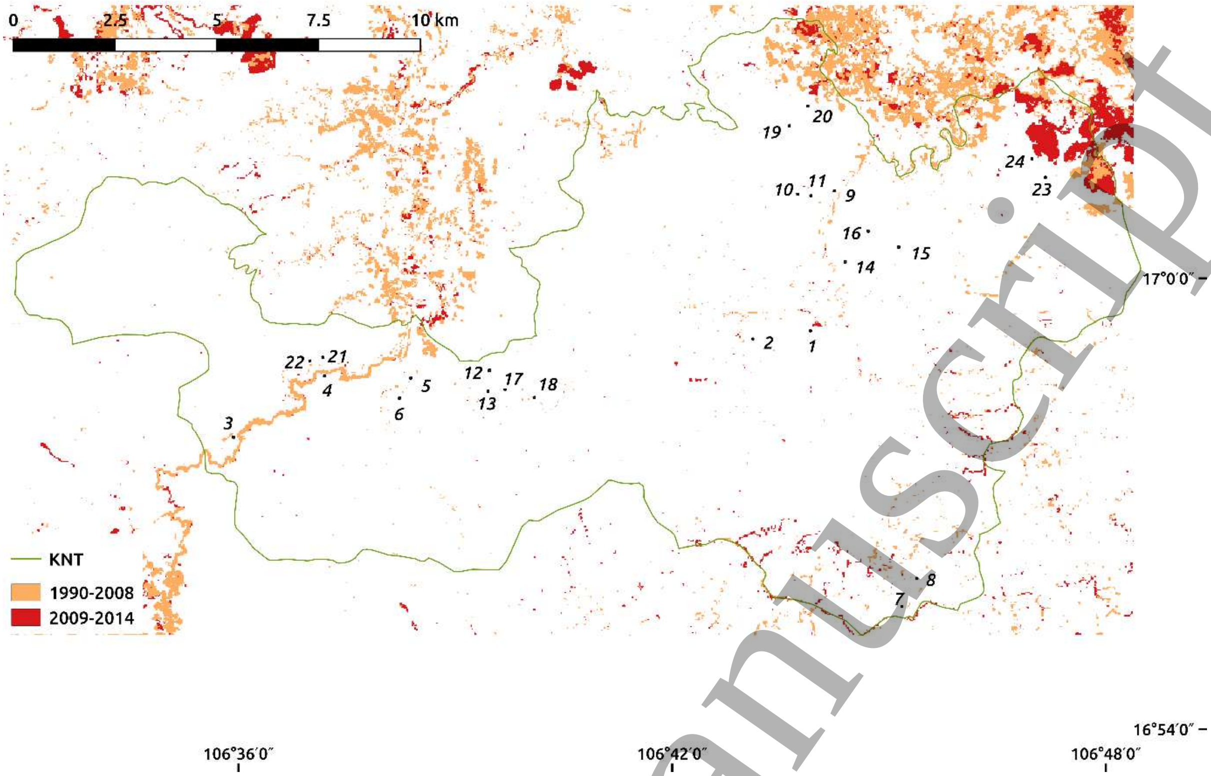

Figure 2. Location of forest plots and forest disturbances. The 24 forest plots are marked and numbered. Boundary of the Khe Nuoc Trong watershed protection forest (established in 2008) is shown with a green line. Forest disturbances identified from our Landsat analysis are shown for two time periods.

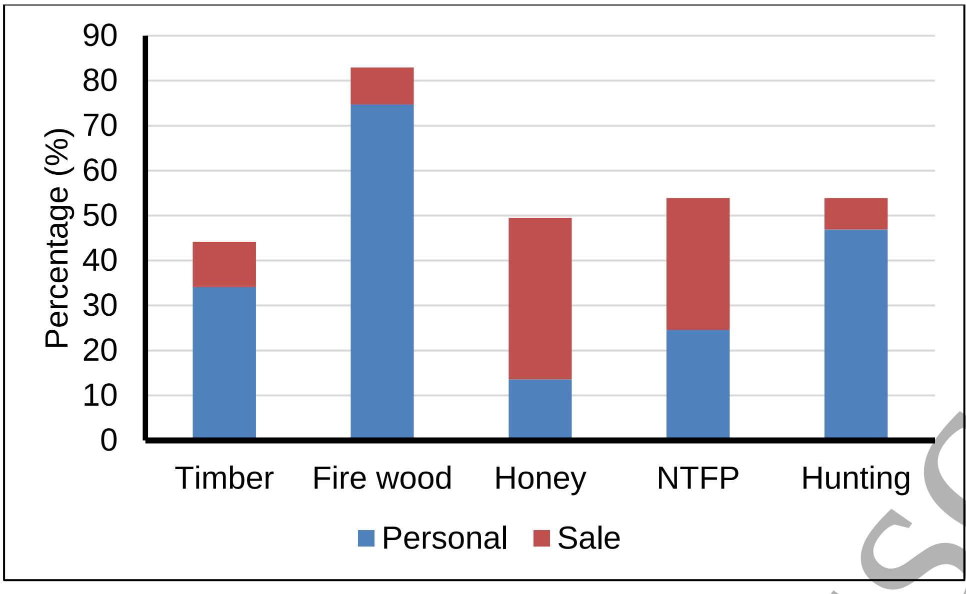

Figure 3. The use of forest resources by local households. Use is split by personal use and for sale. Honey and hunting are shown separately to other Non-Timber Forest Products (NTFPs), which including collection of wild mushrooms, medicinal plants, rattan, and wild vegetables. Results are weighted by the number of households in the three communes.

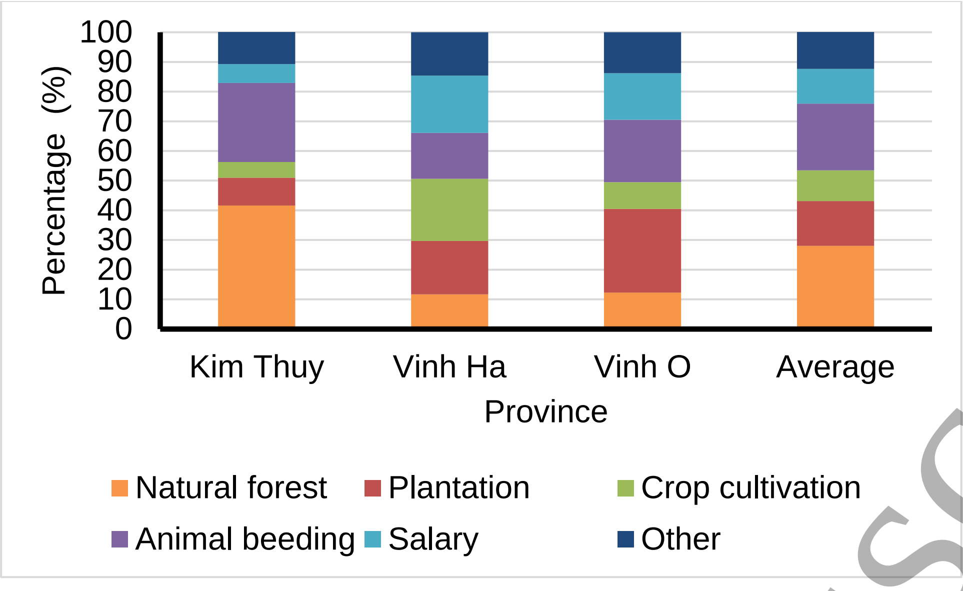

Figure 4. Relative contribution of different sectors to total household income. Results are shown for the three communes and as an average weighted by the number of households in each commune.

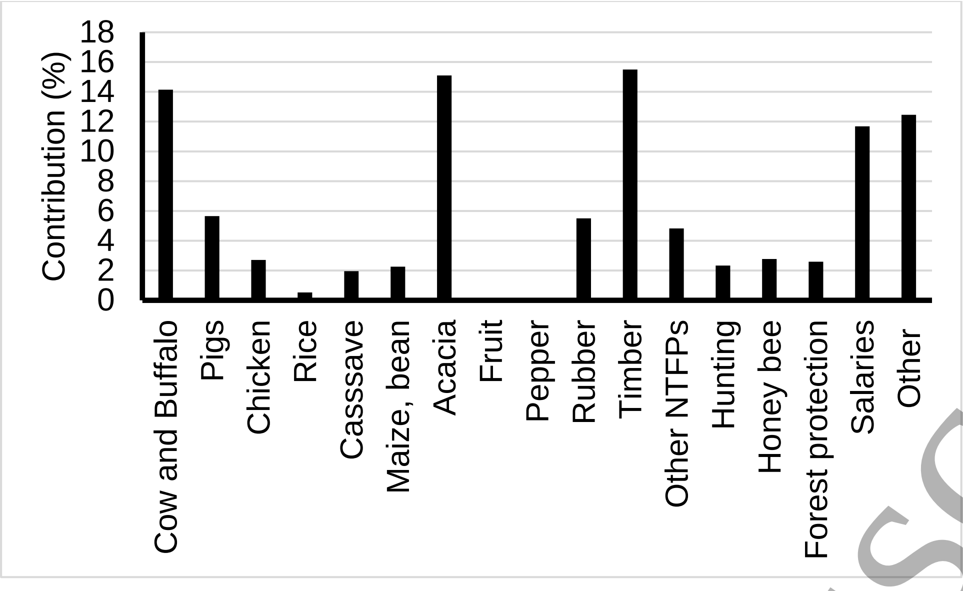

Figure 5. Contribution of different resources to total household income. Results are weighted by the number of households in the three communes.

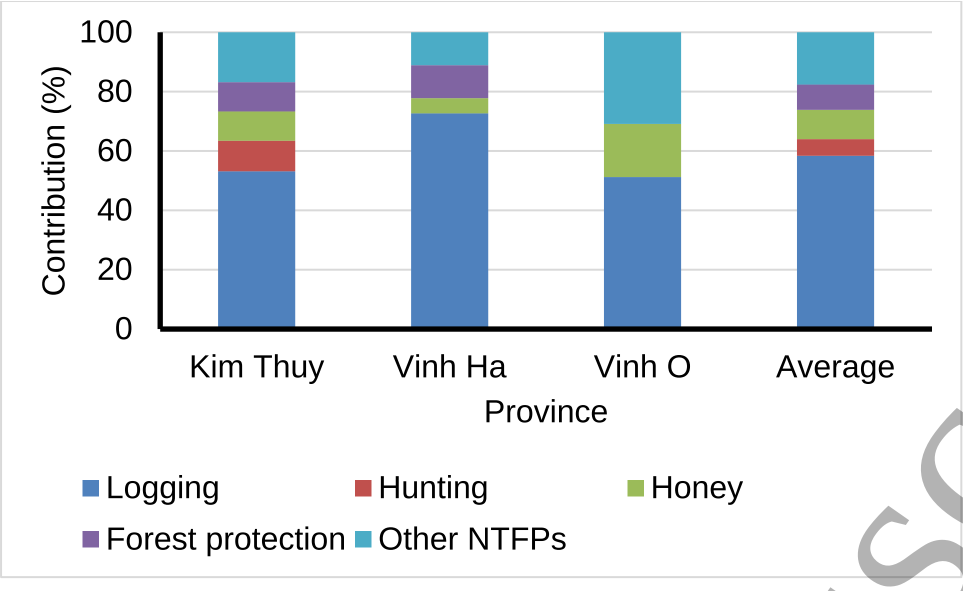

Figure 6. Contribution of different natural forest resources to total income derived from natural forests. Results are shown for the three communes and as an average weighted by the number of households in each commune.

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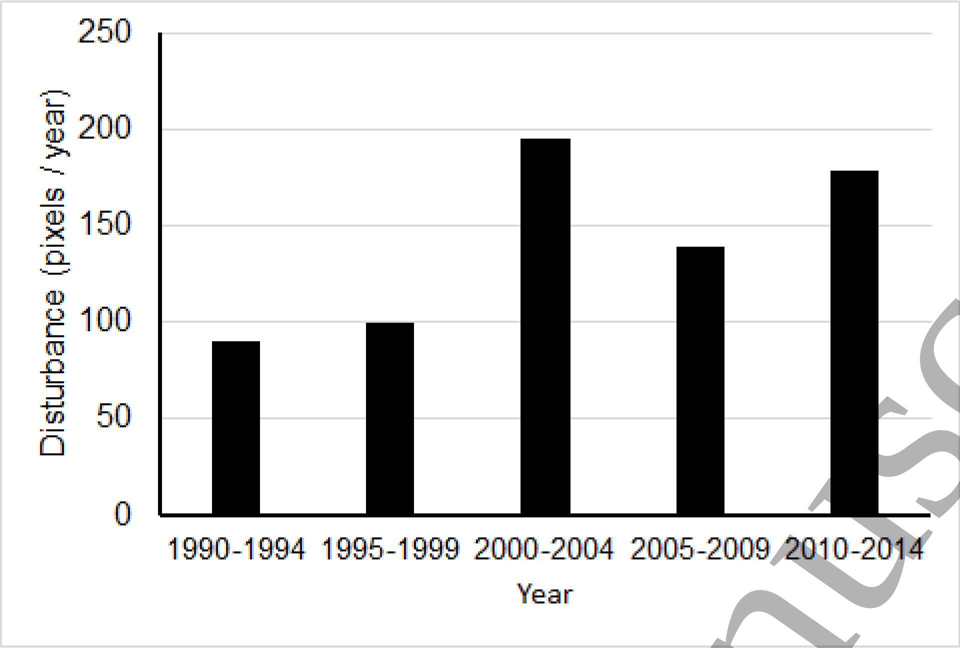

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683 **Figure 7. Forest disturbance in KNT during 1990 to 2014 identified through analysis of Landsat**
684 **images.** Average disturbance reported for 5 year periods. KNT was established as a watershed
685 protection forest in 2008.
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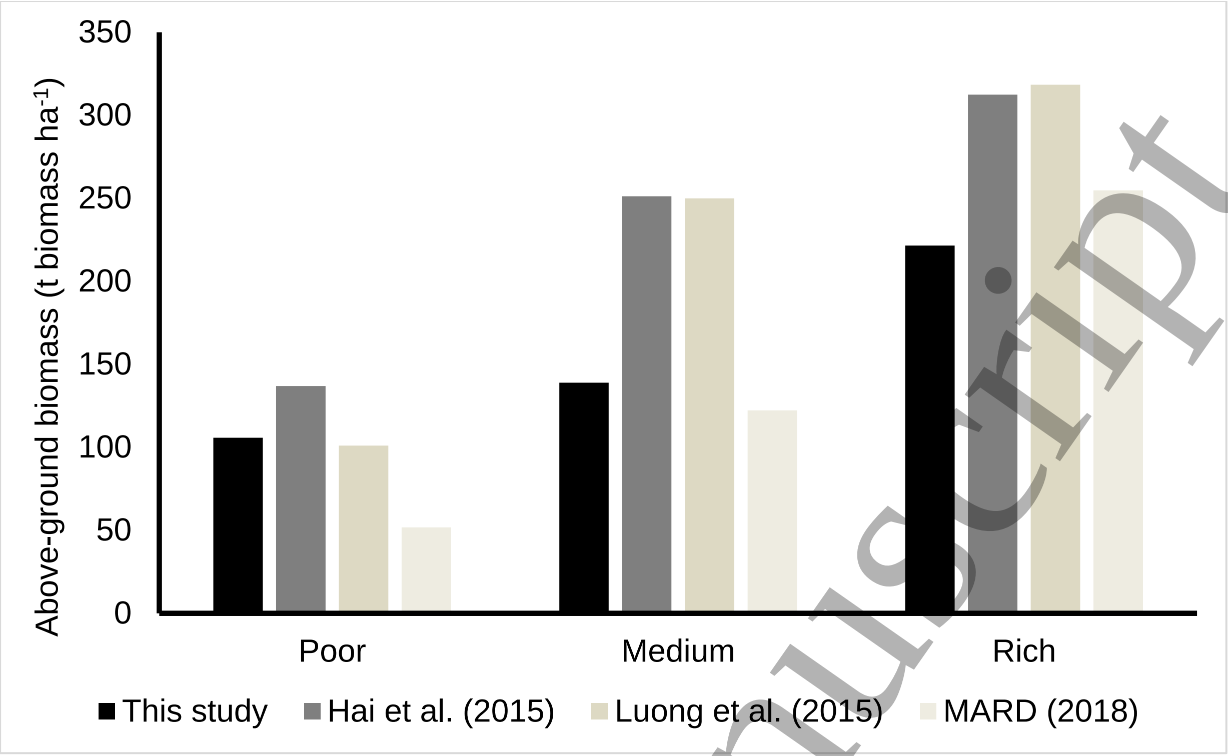

Figure 8. Above-ground living biomass (trees > 5 cm DBH) in poor, medium and rich forests. Results from this study are compared against previous work.

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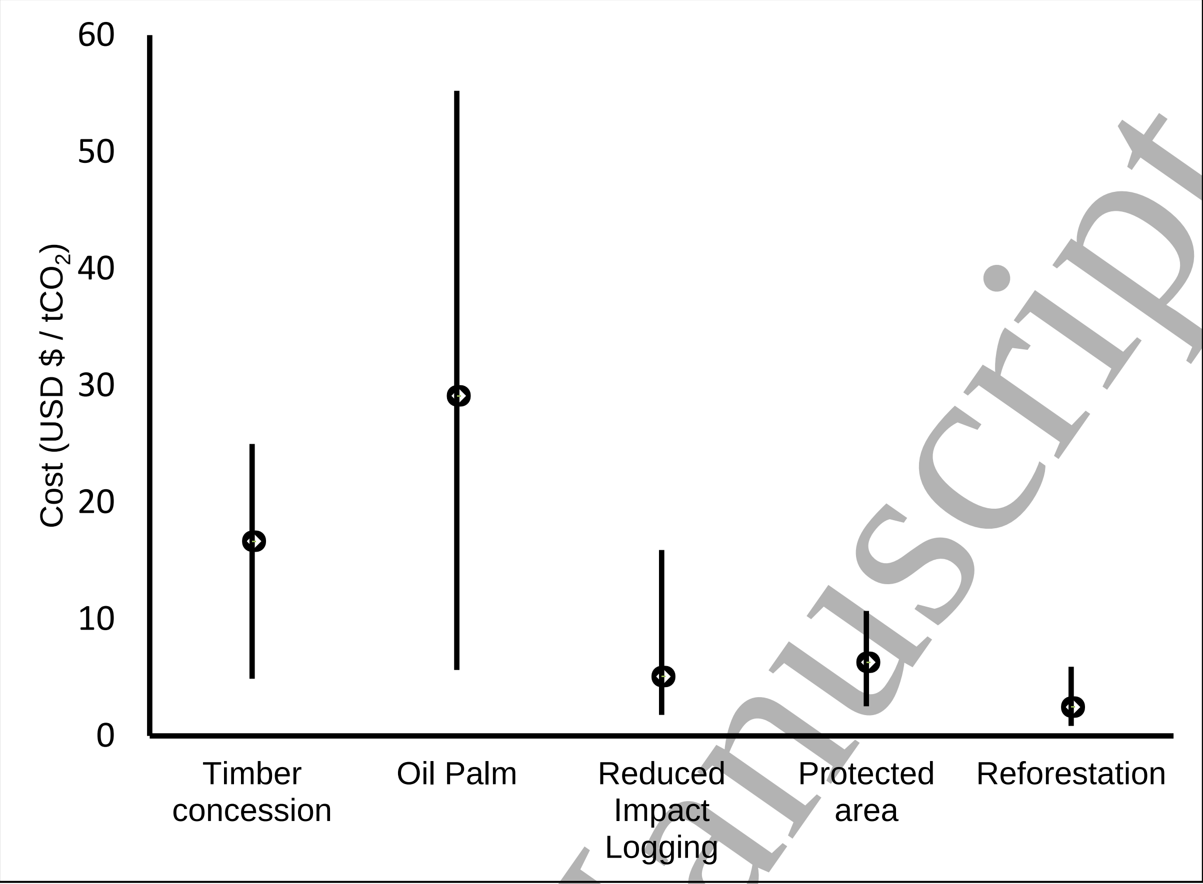

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704 **Figure 9. Comparison of potential opportunity costs for different REDD+ projects in**
705 **Southeast Asia.** Values are synthesised from the literature and reported in Table 4.

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Tables

	Kim Thuy Commune	Vinh Ha Commune	Vinh O Commune
Area (ha)	48,475	16, 403	8, 594
Population	4071	1836	1344
Number of villages	13	9	8
Number of households	1067	561	340
Number of people per household (mean ± standard deviation)	5.2±1.5	3.8 ±1.3	3.9±1.4
Total forest area (incl. plantations)	95.1%	73.4%	97.3%
Natural forest	89.7%	20.9%	44.5%
Plantation forest	5.4%	52.5%	52.8%
Acacia plantation (ha/household) (mean ± standard deviation, maximum in parentheses)	1.0±1.6 (7.5)	0.7±1.1 (6.0)	1.5±1.6 (9.6)
Agricultural land	1.0%	5.2%	1.2%
Agricultural land per household (ha) (mean ± standard deviation)	0.43±0.21	0.25±0.18	0.68±0.34

Ethnic minorities (% of population)			
Kinh	33%	65.7%	5.3%
Van Kieu	67%	34.2%	94.7%
Poverty rate	65.7%	24.5%	74.7%
Average income (US$/household/year, mean ± standard deviation)	$1670±659	$1800±876	$1580±489

Table 1. Details of communes surrounding KNT. Average income using the currency conversion 1USD=VND 23 500.

	Kim Thuy	Vinh Ha	Vinh O
Better	7.8%	27.5%	15.3%
Worse	63.6%	48.8%	52.7 %
Unchanged	28.6%	23.7%	22%

Table 2. Perception of local households on how the quality of natural forest has changed in recent years. Figures are shown separately for the three communes.

	Forest quality type		
	Poor	Medium	Rich
Area (ha)	7004	4968	10323
Basal Area (m^2 m^{-2})	17.3±0.7	21.7±1.7	30.2±1.5
AGB (DBH 5-10 cm) (Mg ha^{-1})	8.9	6.6	9.9
AGB (DBH 10-60 cm) (Mg ha^{-1})	98.1	111.9	149.4
AGB (DBH >60 cm) (Mg ha^{-1})	0	20.5	62.2
Dead wood (Mg ha^{-1})	9.3	13.4	7.9
Total AGB (Mg ha^{-1})	115.1	152.4	229.4
Total biomass (Mg ha^{-1})	140±12	189±18	284±24
Logged basal area (m^2 m^{-2} ha^{-1})	2.9±0.7	3.8±0.9	0.6±0.3
Logged biomass (Mg ha^{-1})	23.4±7.7	34.2±12.0	5.7±3.3
Logged biomass rate (Mg ha^{-1} yr^{-1})	4.3±1.5	6.3±2.3	1.1±0.7
Total logged biomass rate (Mg yr^{-1})	30400±10500	31400±5700	11000±6500
Contribution to total (%)	42%	43%	15%

Table 3. Logging rates in the KNT protected area. Total biomass includes AGB for living stems with DBH≥5 cm, root biomass, standing dead wood and woody debris. Uncertainties are reported as the standard error across the forest plots. Uncertainty in logged biomass and logged biomass rate are estimated through propagating relevant uncertainty terms.

Land use	Location	Opportunity cost (US $ / tCO_2)	Reference
Protected Area	Vietnam	$4.10±0.90	This work
	Indonesia	$10.70	Graham et al. (2017)
	SE Asia	$3.65	Graham et al. (2016)
Reforestation	SE Asia	$2.46	Graham et al. (2016)
	Indonesia	$2.46	Graham et al. (2017)
Timber concession	Indonesia	$15.35	Graham et al. (2017)
Timber concession	SE Asia	$25.00	Fisher et al. (2011b)
Timber concession	SE Asia	$9.63	Graham et al. (2016)
Oil palm concession	Indonesia	$19.93	Graham et al. (2017)
	SE Asia	$20.41	Graham et al. (2016)
Timber & oil palm	SE Asia	$47.00	Fisher et al. (2011b)
Reduced Impact Logging	Indonesia	$6.48	Graham et al. (2017)
	SE Asia	$6.95	Graham et al. (2016)
	Pan-tropical	$1.80	Sasaki et al. (2016)
Timber & rubber	Cambodia	$33.43	Warren-Thomas et al. (2018)
Agriculture & charcoal	Tanzania	$3.9	Fisher et al. (2011a)

Table 4. Opportunity costs of REDD+. Synthesis of previous estimates of the opportunity costs of REDD+.