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Trade-offs and synergies between carbon, forest diversity and forest products in Nepal community forests

THEMATIC SECTION
Forest Ecosystem Services (FES)

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SUMMARY

Reducing emissions from deforestation and forest degradation, the sustainable management of forests and the conservation and enhancement of forest carbon stocks in developing countries ('REDD+') aims to improve local livelihoods and conserve plant diversity while limiting carbon emissions. Yet trade-offs and synergies that exist between supporting livelihoods, protecting plant diversity and maintaining forest ecosystem services are poorly documented. We used forest inventory data and community-group records to assess trade-offs and synergies between carbon, plant diversity and forest products in 19 community forests managed under REDD+ in Nepal. Trade-offs were prevalent for carbon, whereby community forests with relatively high carbon values had relatively low values for plant diversity or forest products provision, and vice versa. Synergies occurred between plant diversity and forest products provision (fuelwood and fodder), suggesting that forests with relatively high plant diversity values were also important for providing critical forest products to local communities. This study shows that conserving forests for carbon should not impinge greatly on the flow of forest resources to at least some local communities; however, promoting carbon storage will not necessarily protect plant diversity. These findings should help guide future REDD+ policy for community forests.

Keywords: carbon, plant diversity, REDD+, trade-offs, synergies, forest products

INTRODUCTION

Reducing emissions from deforestation and forest degradation, the sustainable management of forests and the conservation and enhancement of forest carbon stocks in developing countries ('REDD+') may protect non-carbon forest ecosystem services (ESs) (e.g. timber) while also improving carbon storage. For example, the implementation of REDD+ in Indonesia contributed to soil conservation through improved forest connectivity (Lu *et al.* 2012), while REDD+ has contributed to watershed conservation in sub-Saharan Africa and Costa Rica (Stringer *et al.* 2012).

Community forests (CFs) in developing countries, particularly Nepal, are considered successful models for conserving biodiversity while also providing forest products (e.g. timber and fuelwood) to local communities (Nagendra 2002; Shrestha *et al.* 2010). Yet REDD+, with its emphasis on protecting carbon, can undermine the original objectives of CFs. Various studies of preliminary REDD+ initiatives in CFs have suggested that forest resource access may be restricted and plant diversity lost when there is an overemphasis on protecting carbon (Pandey *et al.* 2014; Poudel *et al.* 2014).

The implementation of REDD+ may result in trade-offs or synergies between ESs and plant diversity. For example, Maraseni *et al.* (2014) found that an increase in carbon corresponded with a decrease in forest products extraction in CFs in Nepal. Other authors (e.g. Chhatre & Agrawal 2009; Visseren-Hamakers *et al.* 2012; Law *et al.* 2015) have demonstrated similar trade-offs between carbon, plant diversity and forest resources in forests managed under REDD+.

However, protecting carbon and plant diversity while still allowing extraction of forest products is possible under certain circumstances, leading to synergies in ES protection (Thompson *et al.* 2012). High plant diversity may enhance the resilience of forest ecosystems, generating greater biomass for carbon and forest products use (Pedro *et al.* 2014).

While REDD+ aims to improve local livelihoods and biodiversity conservation, in addition to increasing baseline carbon, information on trade-offs and synergies between carbon, plant diversity and local livelihoods is lacking, particularly in CFs (Martin *et al.* 2013). While several studies assess trade-offs and synergies at relatively large scales (Maes *et al.* 2012; Cademus *et al.* 2014), fewer studies have accounted for interactions between biodiversity, carbon and forest products at smaller scales relevant to the local implementation of REDD+ (Budiharta *et al.* 2014). Such knowledge should help forest managers limit trade-offs and maximize synergies for the delivery of ESs from forests (Locatelli *et al.* 2014).

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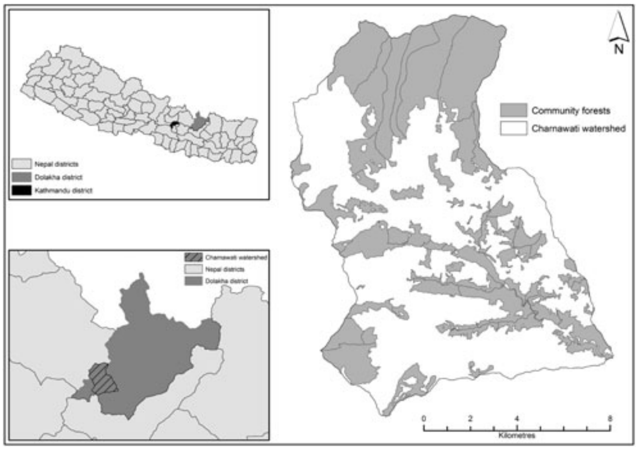

Figure 1 Diagrammatic map of the research site showing the locations of the Charnawati watershed and the 19 community forests.

Here, we examine the trade-offs and synergies between carbon, plant diversity and forest products that are critical to the livelihoods of local people of the Charnawati watershed of Nepal, managed under a REDD+ pilot. The implementation of REDD+ in Nepal was pioneered in the Charnawati, which also represents a showcase of the application of community forestry in the country. Forest products from CFs are critical sources of subsistence for local people in and around Charnawati, which serves as a valuable case study for developing forest management strategies that maximize the protection of plant diversity and carbon while ensuring the ongoing access of local communities to forest products.

The objectives of this study were to identify CFs where positive (mutually high-value) or negative (mutually low-value) synergies exist between carbon, plant diversity (i.e. plant species diversity and stem density) and forest products extraction (i.e. timber, fuelwood and fodder), as well as to identify CFs where trade-offs exist (i.e. have high values for one forest characteristic [e.g. timber] but low values for another [e.g. carbon]) between these attributes.

METHODS

Study area

This study was conducted in 19 CFs in Charnawati watershed (652–3238 m altitude), Nepal (Fig. 1; Table 1), managed under a REDD+ pilot since 2009. Activities under REDD+ include annual carbon monitoring, capacity building and incentives distribution to CF managers. The CFs are generally semi-natural, and forest management activities include enrichment plantation, selective thinning, regulated grazing and harvesting of forest products – mainly timber, fuelwood and fodder/grass (hereafter fodder). Collectively, the CFs encompass diverse vegetation types such as sal (*Shorea robusta*) and chir pine (*Pinus roxburghii*) at lower altitudes and rhododendron (*Rhododendron* species) and oak (*Quercus* species) at higher altitudes.

The duration for which forests have been managed as CFs by local communities varies, and forests are managed by diverse user groups with different ethnicities, needs and socio-economic statuses. To assist in data interpretation, we classified the CFs into high (≥2000 m) or low altitude (<2000 m); long duration of management (local CF management began before or at 2000 CE) or short duration of management (forest management began after 2000 CE); and small (≤1.0 ha of forest per household) or large (>1.0 ha of forest per household) (Table 1).

Data collection and analysis

Vegetation data for carbon and plant diversity were collected through the International Centre for Integrated Mountain Development (ICIMOD) database, which was compiled from forest inventories conducted in February–April 2013. These data included the height and diameter at breast height (dbh) of trees and saplings, the number of seedlings and shrubs and grasses (not including ferns, mosses and lichens) collected from 112 composite plots of 250 m^2 distributed across 19 CFs. A stratified random sampling design was used, whereby forests were stratified into dense (≥70% canopy density) and sparse (<70% canopy density) strata, using a geographic information system (ArcGIS) with Geo-eye satellite images captured in November 2009 (Subedi *et al.* 2010).

Forest products (i.e. annual harvest of timber [m^3], fuelwood [kg] and fodder [kg]) data for 2013 were collected from the logbooks and meeting minutes of CF groups during field visits to Nepal in July–October 2013. We reviewed annual data on the extraction of forest products from the start of the REDD+ project (i.e. 2009–2013), and we used data from 2013 as this represented the change in forest characteristics over a 4-year period and coincided with the end of the REDD+ pilot in the study area. These data were verified through meetings with key members of the executive committee.

Carbon stock, plant diversity and forest product extraction

Per ha carbon included five carbon pools: above- and below-ground tree carbon; saplings and shrubs; herbs and grasses; leaf litter; and soil organic carbon. Aboveground tree and sapling carbon levels were calculated using the equation from Chave *et al.* (2005, p. 92) for moist forest types (Supplementary Material 1; available online).

We used a Nepal-specific biomass equation developed by Tamrakar (2000) to estimate the aboveground sapling (1–5 cm dbh) biomass (eqn (1)):

$$\log(\mathrm{AGSB}) = a + b\,(\log[\mathrm{D}]) \qquad (1)$$

where AGSB = aboveground sapling biomass (kg), log = natural log, a = intercept of the allometric relationship for saplings, b = slope of the allometric relationship for saplings and D = overbark dbh (cm).

Table 1 Main characteristics of community forests included in our study.

Forest number	*Community forest*	*Altitude*	*Time in management*	*Forest size*	*Main vegetation type*
1	Barkhedandapari	Low	Long	Small	Chilaune, *Castanopsis*, chir pine
2	Bhakare	Low	Short	Small	Chir pine
3	Bhitteri	High	Long	Large	Oak, rhododendron, thingure salla
4	Charnawati-1	High	Long	Large	Oak, rhododendron, bluepine
5	Charnawati-2	Low	Long	Small	Sal, chir pine
6	Chyasebhagabati	High	Long	Small	Alder, chir pine, chilaune
7	Dhandesinghdevi	High	Short	Large	Rhododendron, patesalla, *Castanopsis*,
8	Eklepakha	High	Long	Small	Chilaune, *Castanopsis*, bluepine
9	Harisiddhimai	Low	Long	Small	Chilaune, *Castanopsis*, chir pine
10	Jugedarkha	High	Short	Small	Rhododendron, thingure salla, bluepine
11	Kopila	Low	Long	Large	Chilaune, alder, kalikath, rhododendron
12	Majhkharkalisepani	High	Long	Large	Oak, rhododendron, patesalla
13	Mathani	Low	Long	Small	Alder, bluepine, chilaune
14	Napkeyanmara	High	Long	Large	Alder, bluepine, rhododendron, *Castanopsis*
15	Setidevidadar	High	Short	Large	Oak, rhododendron
16	Shivajungbhumethan	Low	Short	Small	Alder, chilaune
17	Sitakunda	Low	Long	Small	Chir pine, sal
18	Thangsadeurali	High	Long	Small	Oak, thingure salla, rhododendron, patesalla
19	Thumkadanda	High	Short	Small	Rhododendron, bluepine, patesalla

The biomass of herbs, litter and grasses was calculated using eqn (2):

$$\mathrm{LHG} = \frac{W_{field}}{A}\,\frac{W_{subsample,dry}}{W_{subsample,wet}} \times 10 \tag{2}$$

where LHG = biomass of litter, herbs and grasses (tonnes ha^{-1}), W_{field} = weight of fresh field sample of litter, herbs and grasses (g) within an area of size A (m^2), $W_{subsample,\ dry}$ = weight of oven-dried subsample of litter, herbs and grasses (g) and $W_{subsample,\ wet}$ = weight of fresh field sample of litter, herbs and grasses (g).

We calculated belowground biomass using a root:shoot ratio, whereby root parts are estimated to contain 20% of total aboveground biomass (MacDicken 1997, p. 84). Total biomass was converted into carbon by multiplying the biomass by the standard value of 0.47 (IPCC 2006). The soil carbon data we used were calculated by ICIMOD in 2010, and we assume that this is representative of 2013 values given that soil carbon does not change substantially over such a short period under the same land-use practices (MacDicken 1997; Martin *et al.* 2013).

Per ha timber (m^3) harvested was calculated from the total quantity of timber harvested from each CF divided by the area of the CF. Timber in CFs is generally harvested using selective logging of standing trees and from fallen trees. The location, tree species to harvest, annual harvestable quantity and the quantity assigned to local forest users are defined in the CF group's forest operational plans. Most of the harvested tree is used for timber, while tree tops and branches are used for fuelwood. Fuelwood is generally extracted from a combination of non-merchantable green and dried wood products such as fallen twigs, stumps and branches. Fodder contains leaves, branches and grass. The per ha annual harvest of fuelwood or fodder (kg) for each CF was calculated by dividing the total quantity of fuelwood and fodder harvested (total number of full and half-head loads [a full head-load is considered to be 35 kg]) by the area of the respective CF.

Plant species diversity was estimated using the Shannon–Wiener diversity index (H') (Magurran 2004). We calculated stem density by counting the number of trees, saplings and seedlings in the survey plots, whereby the average number of stems per plot in each CF was calculated by dividing the total number of stems by the total number of plots. The per ha stem density in each CF was then calculated by multiplying the density of stems in plots by 40.

Trade-offs and synergies between carbon, plant diversity and forest products

We aimed to identify CFs that had high or low values for multiple ESs or between an ES and plant diversity (positive or negative synergies, respectively), or had low values for one ES and high values for another, or a high/low outcome for an ES and plant diversity (i.e. a trade-off). We first analysed pair-wise associations among variables using Spearman's rank order correlation. The strengths of association between variables were classified into five categories based on the correlation coefficient following Dancey and Reidy (2007): zero (0), weak (0.01–0.3), moderate (0.31–0.60), strong (0.61–0.90) and perfect (0.91–1.00).

The purpose of this initial analysis was to determine if, when examining trends across all forests, there were strong synergies (large positive correlation coefficients) or trade-offs (large negative correlation coefficients) across the CFs; that is, for example, did forests with large carbon values consistently have large plant diversity values (positive synergies) or did forests

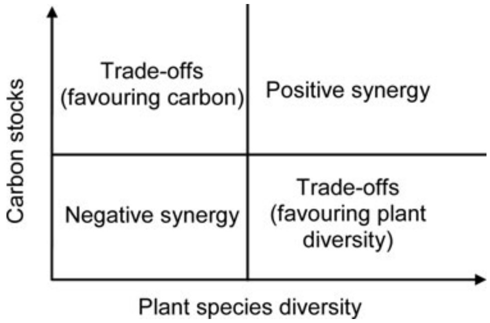

Figure 2 Framework for assessing the trade-offs or synergies between two variables in the context of carbon and plant species diversity. Solid black lines represent the median values. The top left quadrant represents forests with high carbon values (above the median value for carbon) but low values for plant species diversity (below the median value for plant species diversity).

with large carbon values consistently have small plant diversity values (trade-offs)? Importantly, weak correlation coefficients in this analysis are indicative of a much more complex relationship between forest characteristics, suggesting that only some individual forests may have mutually high values of, for example, carbon and forest products, while other forests may have low values of one characteristic, but high values of the other. Hence, weak and strong correlation coefficients uncover fundamentally different, but equally important, dynamics across the group of forests.

We then analysed trade-offs and synergies in ESs and plant diversity using methods described in Luck *et al.* (2009). First, we standardized the numerical values (Supplementary Material 2) of carbon, plant diversity and forest products using Z-scores so that the values of each attribute had a mean of zero and a standard deviation of one. Then we calculated the median value for each attribute, which was used as the threshold value to determine if values were 'high' or 'low' (i.e. above or below the median value, respectively). Finally, we plotted values in pair-wise comparisons to identify trade-offs or synergies for any given CF. For example, in a pair-wise comparison of values for carbon and plant diversity, a given forest may have high values for both (positive synergy), low values for both (negative synergy), a high value for carbon but a low value for plant diversity (a trade-off favouring carbon) or a low value for carbon but a high value for plant diversity (a trade-off favouring plant diversity) (Fig. 2). A number from 1 to 19 was assigned to each CF (Table 1), and these numbers were used as labels in the scatter plots showing trade-offs and synergies.

RESULTS

Correlations between carbon, plant diversity and forest products

There were mostly weak correlations across CFs for carbon, plant diversity attributes and forest products extraction (Table 2). Plant diversity was significantly positively correlated with fuelwood, suggesting forest user groups get this resource mostly from diverse CFs. In general, however, plant diversity attributes were weakly negatively correlated with forest product extraction.

Trade-offs and synergies between carbon, plant diversity and forest products

Trade-offs were particularly prevalent for carbon, in that a CF would have a high carbon value and a low value for plant diversity attributes or forest products, or vice versa (Table 3). This was also true for stem density, where trade-offs existed with timber, fuelwood and fodder. Synergies were more prevalent for plant species diversity and fuelwood and fodder. This suggests that CFs with high plant diversity values were also important for providing some critical forest products to local communities.

CFs 2 (Bhakare) and 17 (Sitakunda) (both low-altitude and small forests) consistently experienced trade-offs favouring carbon over all plant diversity attributes (Fig. 3); that is, they had higher than median carbon values, but lower than median plant species diversity and stem density values. Conversely, CFs 8 (Eklepakha), 12 (Majhakharkalisepani) and 19 (Thumkadanda) (high-altitude and mostly small forests) had higher than median plant diversity values, but lower carbon values. Positive synergies were consistently recorded for CFs 3 (Bhitteri) and 14 (Napkeyanmara) (high-altitude, long duration of management and large forests). This suggests that forest size may be important for whether a trade-off or synergy occurs between carbon and plant diversity.

A positive synergy between carbon and all forest products was recorded for CF 13 (Mathani) (a low-altitude and small forest), whereas consistent trade-offs favouring all forest products were recorded for CFs 18 and 19 (high-altitude and small forests) and favouring carbon for CF 4 (Charnawati-1) (a high-altitude and large forest) (Fig. 3). This suggests that small CFs at higher altitudes may be relatively more important for providing forest products, while large forests around the same altitude are important for protecting carbon.

CFs 13 and 19 (small forests) had positive synergies between plant species diversity and all forest products, while CF 4 (a high-altitude and large forest) had negative synergies (Fig. 4). CF 18 showed trade-offs favouring all forest products over plant species diversity. CF 19 consistently had positive synergies between stem density and all forest products, while consistent trade-offs favouring all forest products over stem density existed for CFs 13 and 18 (low-altitude and small forests). This implies that plant species diversity and stem density had inconsistent trade-offs and synergies with forest products.

DISCUSSION

Relationships between carbon and plant diversity

Forest carbon was weakly negatively correlated with plant diversity. Higher plant diversity may coincide with higher

Table 2 Results of Spearman's rank order correlations between carbon, plant diversity and forest products. *Correlation is significant at the 0.05 significance level (two-tailed).

Carbon, plant diversity attributes and forest products	*Correlation (r_s) with p-value*	*Strength of association*
Carbon and plant species diversity	-0.14 ($p = 0.54$)	Weak
Carbon and stem density	-0.28 ($p = 0.24$)	Weak
Carbon and timber	0.01 ($p = 0.98$)	Weak
Carbon and fuelwood	-0.06 ($p = 0.81$)	Weak
Carbon and fodder	0.05 ($p = 0.83$)	Weak
Plant species diversity and timber	-0.16 ($p = 0.50$)	Weak
Plant species diversity and fuelwood	0.48^* ($p = 0.03$)	Moderate
Plant species diversity and fodder	0.26 ($p = 0.27$)	Weak
Stem density and timber	-0.37 ($p = 0.11$)	Moderate
Stem density and fuelwood	-0.22 ($p = 0.34$)	Weak
Stem density and fodder	-0.26 ($p = 0.27$)	Weak

Table 3 The number of community forests having trade-offs and synergies between carbon, plant diversity and forest products.

Forest attributes	*Trade-offs (higher values of A)*	*Trade-offs (higher values of B)*	*Community forests with trade-offs*	*Positive synergy*	*Negative synergy*	*Community forests with synergies*
(A) Carbon and (B) plant species diversity	5	5	10	5	4	9
(A) Carbon and (B) stem density	6	6	12	4	3	7
(A) Carbon and (B) timber	5	5	10	5	4	9
(A) Carbon and (B) fuelwood	6	6	12	4	3	7
(A) Carbon and (B) fodder	4	4	8	6	5	11
(A) Plant species diversity and (B) timber	6	6	12	4	3	7
(A) Plant species diversity and (B) fuelwood	3	3	6	7	6	13
(A) Plant species diversity and (B) fodder	4	3	7	6	6	12
(A) Stem density and (B) timber	5	5	10	5	4	9
(A) Stem density and (B) fuelwood	6	6	12	4	3	7
(A) Stem density and (B) fodder	6	6	12	4	3	7

carbon stocks in some natural forests (Day *et al.* 2014), but there was no evidence of this in our study. This may be due to the prevalence of plant species such as chir pine and alder, which have relatively low carbon storage capacities in the research site. In some cases, lower carbon stocks can exist even in highly diverse forests if the dominant tree species has a low carbon storage capacity (Kirby & Potvin 2007; Baral *et al.* 2009).

Mandal *et al.* (2013) and Kimaro and Lulandala (2013) found negative relationships between carbon and plant species diversity. Forest thinning through selective removal of large trees may reduce carbon without impacting negatively on plant species diversity (Widenfalk & Weslien 2009), and the majority of CFs in our study apply thinning to extract large trees.

We found a weak negative association between carbon and stem density, implying that the size and average carbon storage capacity of particular trees is more important to carbon stocks than simply the number of plants present. Pandey *et al.* (2014) estimated the maximum average per ha carbon storage capacity of chir pine, *Schima–Castanopsis*, *Rhododendron–Quercus* and sal trees in the research site as 91.4, 87.9, 102.9 and 121.2 tonnes, respectively. Murphy *et al.* (2013) found non-significant relationships between carbon and stem density, while Wang *et al.* (2011) recorded less carbon in forests with greater stem density, mainly due to the prevalence of smaller trees. It appears that the growth stage of forests may determine the carbon–stem density relationship.

In terms of trade-offs and synergies, there were varying results across CFs and forest attributes. Positive synergies between carbon and plant diversity existed mostly in high-altitude and large CFs. These forests are therefore important for maintaining plant diversity, while also storing relatively high levels of carbon, and large forests may buffer adverse impacts on plant species diversity. Trade-offs favouring carbon over plant species diversity occurred mostly in small forests located at low elevation. Low-altitude (i.e. sub-tropical) forests support plant species with higher carbon storage capacities (Baral *et al.* 2009), although overall plant species diversity is relatively low.

Relationships between carbon and forest products

There was a weak positive correlation between carbon and the amount of timber and fodder extracted from forests. A higher level of forest products extraction generally corresponds with

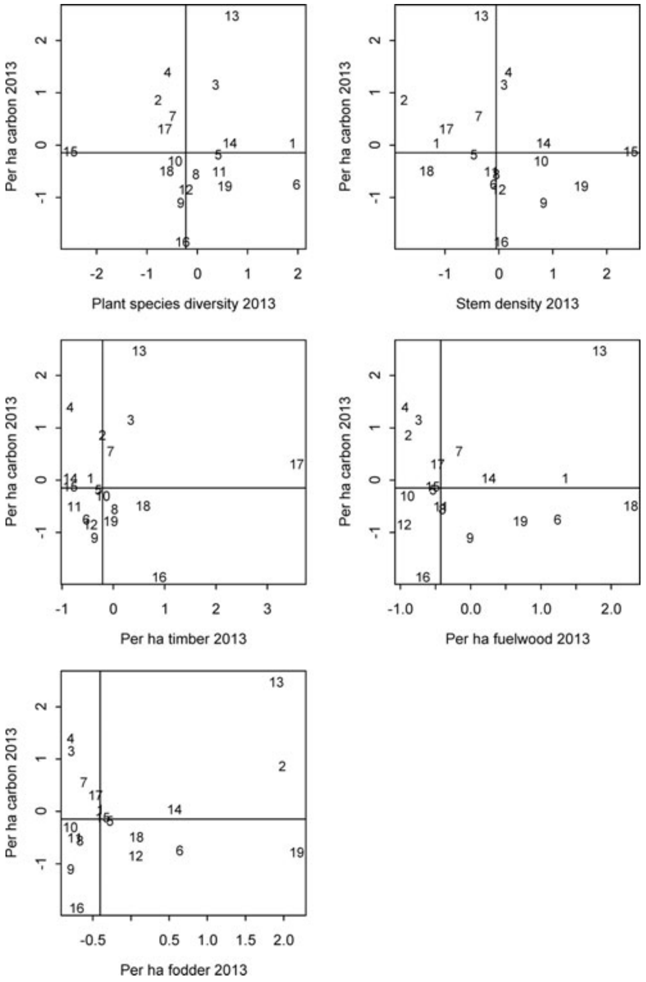

Figure 3 Community forests with trade-offs and synergies between carbon, plant diversity attributes and forest products. Numerical values along the x- and y-axes are Z-scores. Forests (represented by forest number) in the top left and bottom right quadrants indicate trade-offs, while forests in the top right and bottom left quadrants indicate positive and negative synergies, respectively.

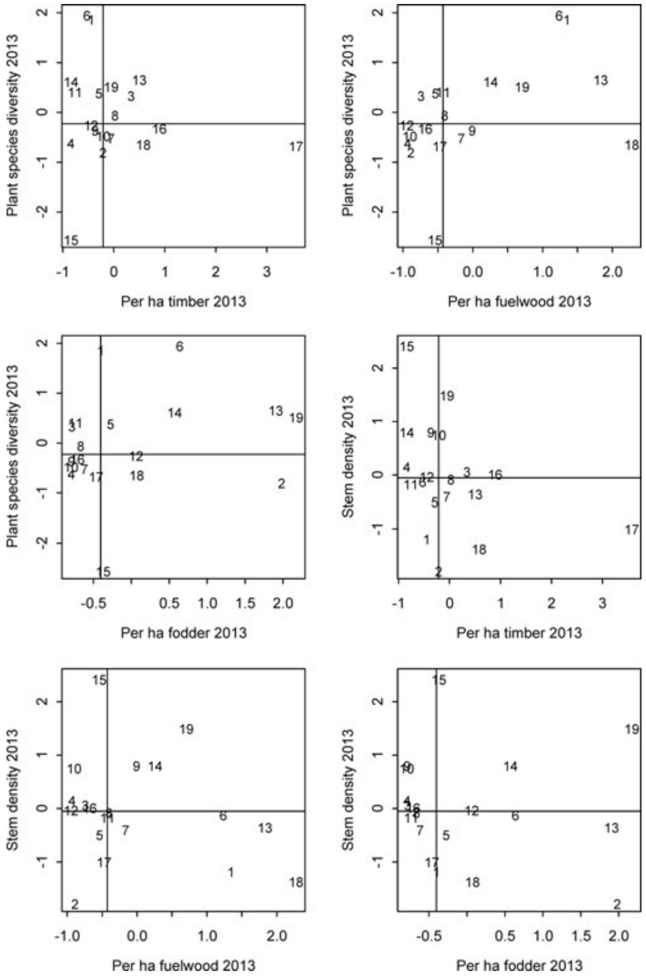

Figure 4 Community forests with trade-offs and synergies between plant diversity attributes and forest products. Numerical values along the x- and y-axes are Z-scores. Forests (represented by forest number) in the top left and bottom right quadrants indicate trade-offs, while forests in the top right and bottom left quadrants indicate positive and negative synergies, respectively.

lower carbon stocks (Schwenk *et al.* 2012). However, there was no evidence of this in our study for timber or fodder. A positive relationship between carbon and timber extracted could be due to the application of sustainable harvesting techniques by local people. Adoption of reduced-impact logging for timber extraction may not reduce carbon (Nghiem 2014). In the study area, timber is extracted from selected tree species based on an annual allowable harvesting limit in the majority of CFs. This means that timber extraction may not impede overall forest carbon (Putz *et al.* 2012). Also, the application of post-harvest restoration and planting can enhance carbon despite the removal of timber (Perez-Garcia *et al.* 2005).

Fodder extraction in this study area may not negatively impact carbon storage potential because fodder is generally extracted from leaves and branches without felling standing trees. However, further assessment is required to test this relationship owing to limitations in the allometric equation as applied in Nepal. Because the equation is based only on tree height and dbh, it does not account for other changes in tree biomass (biomass discount factor), such as removal of leaves and branches. Barshila *et al.* (2013) and Singh and Sundriyal (2009) also found that the extraction of fodder has a small effect on carbon. We found a very weak negative relationship between carbon and fuelwood. While fuelwood is extracted throughout most of the year in the majority of CFs, this currently does not appear to be having a significant negative impact on carbon. However, this needs to be carefully monitored in future years.

Trade-offs and synergies between carbon and forest products extraction varied across CFs. Trade-offs favouring carbon over all forest products occurred mostly in larger forests under short and long durations of management, and at low and high altitudes. This demonstrates the resilience of large forests to local community demands, but this resilience is dependent on future levels of demand, the management strategies implemented to ensure sustainable harvesting practices and changes in natural disturbances such as insect and disease outbreaks and forest fires.

While the relationships between carbon and forest product extraction reflect the level of forest dependency of local people, they are also influenced by access to alternatives to forest products (e.g. private sources), forest product distribution rules and local perceptions of the importance of protecting carbon (Bhattarai *et al.* 2012; Bluffstone *et al.* 2013). For example, Chhatre and Agrawal (2009) found positive synergies between carbon and forest product extraction in larger CFs when sustainable resource use practices were adopted. Similarly, Chand *et al.* (2015) found a positive relationship between forest products and carbon, and the authors argued that managing CFs for certain forest products may enhance carbon.

Relationships between plant diversity attributes and forest products

Plant species diversity was positively related to the harvesting of fuelwood and fodder, but not timber. This suggests that a greater amount of fuelwood and fodder was extracted from more diverse forests. Extraction of forest products from green and standing trees is restricted in the majority of CFs in the research site. Fuelwood is extracted mainly from branches, dead twigs and stumps, while fodder is extracted from leaves and branches without felling standing trees. Removal of these resources likely has a small effect on the number and diversity of living plants (Måren *et al.* 2014), although over the long term it may adversely impact overall plant diversity. Shrestha *et al.* (2013) in Nepal observed no impact on the plant diversity of the fodder extraction from tree branches and leaves, and found that the removal of fodder up to a certain amount (i.e. intermediate disturbance) may actually result in an opening in the forest canopy, which can lead to greater plant species diversity.

There was a weak negative correlation between timber extraction and plant species diversity. In our study area, timber is generally extracted from live-standing trees of specific tree species (e.g. sal and chir pine in low-altitude forests and thingure salla [*Tsuga dumosa*] and bluepine [*Pinus wallichiana*] in high-altitude forests) with certain qualities such as strength, durability and straightness. Repeated removal of live-standing trees may eventually lead to local declines of particular plant species (Hall *et al.* 2003). Timber extraction may also have negative effects on plant diversity due to physical damage to the natural regeneration of seedlings during timber harvesting (Tavankar & Bonyad 2015). This is highly relevant to this research site since timber extraction is generally performed manually (involving people felling and removing logs).

CFs that had trade-offs favouring timber over plant diversity were mostly small forests at high altitude. The prevalence of such trade-offs in high-altitude forests may be due to their slow growth and the fact that the introduction of new plant species is often unsuccessful owing to unsuitable ecological conditions. The positive synergies in some CFs between plant diversity and fuelwood or fodder may be the result of forest users planting multipurpose plant species that provide resources while also increasing overall plant diversity. This was observed mostly in management of long duration and larger forests. Such activities may occur in larger CFs because there is enough space for planting multiple tree species, while greater forest management experience may lead to more effective management strategies.

Some studies have shown a decline in stem density in forests with the removal of fuelwood and fodder from live-standing trees (Jiang *et al.* 2015; Tavankar & Bonyad 2015), but there was little evidence of this occurring in our study area. Stem density is generally associated with the intensity of silviculture practices such as thinning (Thomas *et al.* 1999), which is adopted by almost every CF in Charnawati to extract fuelwood and timber.

CONCLUSION AND POLICY IMPLICATIONS

Both trade-offs and synergies occurred across CFs for carbon, plant diversity and forest products. Trade-offs were particularly prevalent between carbon and plant diversity and certain forest products, while synergies existed between plant diversity, fuelwood and fodder.

The patterns of trade-offs and synergies varied across CFs depending on forest size, time in management and altitude, and these factors reflect differences in forest vegetation types, management practices and local needs. For example, larger forests in high-altitude regions have high values for carbon and plant diversity, with greater capacity to withstand the pressure of forest products removal. This suggests more broadly that larger forests could be targeted to provide local communities with resources without undermining carbon storage potential or plant diversity conservation. Despite being small, low-altitude forests had high carbon values, likely owing to the presence of fast-growing tree species located in a sub-tropical climatic zone with deep and fertile soils (Maraseni & Pandey 2014). This suggests that smaller forests elsewhere may play an important role in carbon storage, and could be protected primarily for this purpose, rather than to provide forest products.

The results indicate that within Charnawati and in similar regions globally, an integrated approach to forest management that includes sustainable harvesting of forest products and livelihood improvement activities outside of forests is required to protect carbon, plant diversity and forest resources. The conservation of biodiversity and safeguarding the rights of local people are central to current REDD+ debates, and also need to be integrated into existing local forest management practices as directed by their operational plans. Compensating local people for growing trees in private forests, introducing alternative fuel sources for cooking and implementing non-forest-based income-generating activities targeting land-poor forest users can enhance carbon and conserve biodiversity.

Without REDD+-influenced management of forests, we suggest that forest managers will have fewer incentives to limit the extraction of forest products, leading to less protection of carbon and plant diversity. It is also likely that forest management will not account appropriately for the different values of forests (e.g. natural, social and economic), and there would be less chance of integrated management across a suite of forests.

This study includes the plant diversity measures that are most relevant to changes in carbon in CFs, but we acknowledge that other biodiversity measures such as fauna diversity may lead to different synergy and trade-off relationships between these forest characteristics. Nevertheless, this study provides a foundation upon which further systematic assessment of trade-offs and synergies can be conducted for other forest ESs in CFs or other management regimes in different regions. The results of this study should help policy makers and planners in Nepal and other countries to design improved REDD+ initiatives and forest policies that generate multiple benefits for local communities, improve plant diversity conservation and reduce carbon emissions.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

ETHICAL STANDARDS

This article does not contain any studies with animal subjects. Informed consent was obtained from all residents of the local communities in Nepal that contributed information to our study. Interviews with local residents were conducted under the guidance and approval of the Human Research Ethics Committee of Charles Sturt University (Approval #410/2013/07).

Supplementary Material

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