A Meta-Analysis on the Impacts of Partial Cutting on Forest Structure and Carbon Storage

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Abstract

Partial cutting, which removes some individual trees from a forest, is one of the major and widespread forest management practices that can significantly alter both forest structure and carbon (C) storage. Using 744 observations from 81 studies published between 1973 and 2011, we synthesized the impacts of partial cutting on three variables associated with forest structure (i.e., mean annual growth of diameter at breast height (DBH), basal area (BA), and volume) and four variables related to various C stock components (i.e., aboveground biomass C (AGBC), understory C, forest floor C, and mineral soil C). Results show that the growth of DBH elevated by 112% after partial cutting, compared to the uncut control, while stand BA and volume reduced immediately by 34% and 29%, respectively. On average, partial cutting reduced AGBC by 43%, increased understory C storage by 392%, but did not show significant effects on C storages on forest floor and in mineral soil. All the effects on DBH growth, stand BA, volume, and AGBC intensified linearly with cutting intensity (CI) and decreased linearly with the number of recovery years (RY). In addition to the strong impacts of CI and RY, other factors such as climate zone and forest type also affected forest responses to partial cutting. The data assembled in this synthesis were not sufficient to determine how long it would take for a complete recovery after cutting because long-term experiments were scarce. Future efforts should be tailored to increase the duration of the experiments and balance geographic locations of field studies.

1 Introduction

Forests cover 31% of the total land area globally and play a major role in the global carbon (C) cycle (FAO, 2010; Pan et al., 2011). They experience various disturbances, often with increasing frequency and severity unseen in recorded history (Asner et al., 2005; DeFries et al., 2010; Masek et al., 2011). Partial cutting, one of the major forest management activities in many regions of the world (Houghton, 2005; Peres et al., 2006), removes some tree individuals from forests to serve various purposes including enhancement of wood production, management of species composition and stand structure, and reduction of fire risk (Kolb et al., 1998; Harvey et al., 2002; Frey et al., 2003; McDowell et al., 2006; Campbell et al., 2009). Partial cutting is known to cause significant impacts on both forest structure and functions (Reich, 2011; Goetz et al., 2012). It can alter tree spacing, density, and size distribution, and affect carbon exchange between the biosphere and the atmosphere (Vesala et al., 2005; Dwyer et al., 2010; Huang and Asner, 2010).

The impact of forest cutting, especially partial cutting, has been identified as one of the major knowledge gaps in regional and global C accounting (Liu et al., 2011; Goetz et al., 2012). Most studies have been performed at plot scale (e.g., Bunker et al., 2005;Vargas et al., 2009; Navarro et al., 2010), and the experimental results from individual studies are highly variable mainly because of the differences in cutting intensity (CI) and length of recovery years (RY) after cutting. For example, some studies reported substantial increases in the growth of tree diameter at breast height (DBH) (Guariguata, 1999; Vesala et al.,2005), stand basal area (BA) (Vargas et al., 2009), tree volume (Curtis et al., 1997; Smith, 2003), and some C stocks (Lee et al., 2002; Kunhamu et al., 2009; Horner et al., 2010; Navarro et al., 2010) following partial cutting, whereas many showed insignificant or opposite impacts on these forest properties (Sawadogo et al., 2005; Chan et al., 2006; Lindquist, 2007; Peña-Claros et al., 2008; Skovsgaard, 2009; Campbell et al., 2009). The diversified and seemly inconsistent results across various studies preclude our comprehensive understanding of forest cutting and hinder the extrapolation of experimental results to predict long-term change of forest ecosystem and C dynamics at regional and global scales (Luo et al., 2006).

To our knowledge, two syntheses examining the changes of soil C stock after forest cutting in temperate forests (Nave et al., 2010) and global forests (Johnson and Curtis, 2001) have been conducted to date. Both studies found the change of soil carbon in mineral soils was insignificant. The C storage on the forest floor either decreased (Nave et al., 2010) or changed insignificantly (Johnson and Curtis, 2001) following forest cutting. Nevertheless, these two syntheses concentrated on soil C dynamics, and their focus was on clear cutting rather than partial cutting. Apparently, a comprehensive assessment on the impacts of partial cutting on the structure and C dynamics in forest ecosystems is needed for a better understanding and quantification of its role in the C cycle (Pregitzer and Euskirchen, 2004; Huang and Asner, 2010; Goetz et al., 2012). In this paper, we analyzed and synthesized 744 observations from 81 field studies published between 1973 and 2011 and examined changes in various forest structural characteristics and C stock components induced by partial cutting.

2 Methods

2.1 Data Sources

Data were collected from relevant scientific papers published by the end of December 2011. We searched the online databases Web of Knowledge (http://isiknowlegde.com) and Google scholar (http://scholar.google.com) for available papers published in the English language using keywords “thinning,” “selective cutting,” “partial cut,” “harvesting,” “management treatment,” or “silvicultural treatment” (in title, abstract, or keywords) and theme “forest”. The following three criteria were used to select data from papers for this synthesis. First, studies without control (i.e., an uncut forest plot) were excluded. Without control plots, it is impossible to do the paired comparison to analyze the relative changes induced by partial cutting over time. Second, modeling studies were excluded because our synthesis was based on field observations. Finally, papers that did not report CI and those dealing with repeated cuttings were also excluded. After scanning all the papers returned, we compiled a database of 81 papers published between 1973 and 2010 that reported the impacts of partial cutting on either the forest structure and/or C storage (Fig. S1).

Cutting intensity (i.e., CI) has been defined differently in the collected 81 publications, using either the amount of volume, BA, or stems removed from or remained in the stand. In this paper, we define CI as the removed (not remaining) fraction of volume, stand BA, or stems in the stand during cutting operations. If the CI is defined otherwise in the original papers, we have converted it to our definition.

The raw data were either extracted from published tables or obtained by digitizing published graphs using GetData Graph Digitizer 2.24 (free software downloaded from http://getdata-graph-digitizer.com). The final constructed dataset consists of 744 observations, with the longest RY being 42 years after cutting. It includes three variables associated with forest structure (annual mean DBH growth, stand BA, and volume) and four variables related to various C stock components (aboveground biomass C (AGBC), understory C storage, forest floor C, and mineral soil C (with a depth of 0-15 cm)) (Table S1). We defined the depth of mineral soil as 0-15cm in this analysis because about 82% of the studies reported the soil C sampled in this layer. The other studies (*i.e., Yang et al., 2001; Gundale et al., 2005*) that provided soil C at the depth of 0-10cm were also utilized directly without further transformation in order to include observations as many as possible. In addition, each record includes information regarding its geographic location (longitude and latitude), climate information (tropical, subtropical, Mediterranean, temperate continental, temperate maritime, and boreal), forest type (coniferous, broadleaf, and mixed), and definition of CI (defined by stem number, stand BA, or volume) which were easily extracted from the publications. If the paper did not report the climate information, we determined it according to the geographic location of the study sites.

2.2 Meta-analysis

The percent relative change (RC) in any of the seven variables following partial cutting was calculated as follows (Laganière et al., 2010; Power et al., 2011):

$$RC = (CUT_t - CON_t) / CON_t * 100$$

where CUT_t is the value of a given variable from the cutting stand at time *t*, and CON_t is the value from the control at time t. Thus, negative RC indicates a negative response to partial cutting and positive RC indicates a positive response.

Many of the studies did not report any measure of variance for the response variables that we were interested in. Thus, in order to include as many studies as possible, an unweighted meta-analysis was used in this paper, in which the response effects were not weighted by sample size (Gurevitch and Hedges, 2001; Guo and Gifford, 2002). The nonparametric resampling was utilized to generate bias-corrected bootstrapped approximate 95% confidence intervals from 1,000 randomizations in SPSS PASW Statistics 18 (SPSS Inc.). The estimated effects were considered statistically different from zero if the zero did not fall into the 95% confidence interval, and the two effects were considered significantly different if the confidence intervals of them did not overlap.

To investigate the impacts of cutting intensity on forest properties, all data were grouped into three CI categories: light ($CI<34\%$), moderate ($34\%\leq CI< 67\%$), and heavy (CI≥67%). We further examined the recovery of these properties after cutting practices by grouping the observations into three recovery years (i.e., RY) according to the number of years after cutting: short (RY≤5 years), medium (5 years <RY≤10 years), and long (RY>10 years) experiments. We put all experiments longer than 10 years into one category because there were not enough observations in this category to divide it further. These grouped analyses were performed on the variables with sufficient observations (i.e., DBH growth, stand BA, volume, and AGBC).

To determine if including other biophysical factors (in addition to CI and RY) can reduce unexplained variation in the observed responses, we examined the relationships between the relative changes and the other underlying factors including climate zone, forest type, and definition of CI (using stand BA, volume, or stems) for all the four variables with sufficient observations (i.e., DBH growth, stand BA, volume, and AGBC). For the convenience of quantitatively estimating their relationship, we treated these categorical factors (i.e., climate zone, forest type, and CI definition) as dummy variables (Gujarati, 1970). Because CI and RY usually play a dominant role in both the overall changes and the recovery of the forest ecosystem after partial cutting (Scheller et al., 2011), they may overshadow the impact of the other factors on the general response patterns. To reduce this effect, we calculated the partial correlation coefficients between all of these dummy variables and relative changes while holding CI and RY as the control variables in SPSS PASW Statistics 18 (SPSS Inc.).

3 Results

3.1 Overall Direction and Magnitude of the Changes in Forest Structure and C Stocks

The relative changes of various forest structural attributes and C stock components following partial cutting varied in direction and magnitude (Fig.1 and Table 1). For stand BA and volume, a negative effect was the most frequently observed pattern. By contrast, a positive effect was mostly observed in DBH growth. Overall, partial cutting decreased stand BA and volume significantly by 34 and 29 percent, respectively, but increased DBH growth by 112 percent relative to the uncut controls in our compiled dataset. Closely related to the structure dynamics, the C stored in AGBC reduced significantly by 43 percent, while the C stored in understory elevated substantially by 392 percent, compared with the uncut controls. However, decreases in the C stocks of both forest floor (reduced by 9%, P=0.18) and mineral soil (declined by 3%, P=0.37) were not significant (Table 1).

3.2 Factors Affecting the Responses of Forest Structure and C Pools to Partial Cutting

CI and RY played a major role in the response of forest ecosystem to partial cutting (Fig. S2 and Table 2). CI had a significant and negative correlation with stand BA, volume, and AGBC, while RY related significantly and positively to all of them. By contrast, the relative change of DBH growth was significantly and positively correlated with CI (r=0.23, P<0.01), and significantly and negatively with RY (r=-0.18, $P < 0.05$). As for the relationships between CI or RY and understory C storage, forest floor C, or mineral soil C, only a positive correlation between CI and understory C (r=0.60, $P < 0.01$) was significant.

Factors other than CI and RY also contributed to the observed variations in both forest structure and C pools (Table 2). For the two variables with sufficient observations (i.e., DBH growth and stand BA), our results show that the positive effect of partial cutting on DBH growth was more intensive in the broadleaf trees than in conifer ones compared with the uncut controls (r=0.22, P<0.01) (Fig.4 and Table 2) probably because of the greater light improvement for the remaining trees in broadleaf forests compared to coniferous forests after partial cutting (Hale, 2003). Nevertheless, the changes in stand BA after partial cutting did not differ significantly with forest type (Fig. 4 and Table 2), most likely due to its strong dependence on cutting intensity (Scheller et al., 2011). We found the increase in DBH growth was lower in subtropical forests than that in most others (r=-0.24, P<0.01) (Fig.5 and Table 2), which can also be mainly explained by relatively lower light enhancement for the remaining trees in subtropical forests compared to other forests after cutting practices (Hale, 2003). In addition, the changes of DBH growth and stand BA were overall weaker in boreal forests relative to most other regions (Fig.5 and Table 2), probably due to the lower vegetation productivity under this climate condition. It's interesting to notice that the definition of CI was closely linked to the relative changes in DBH growth, stand BA, volume, and AGBC, indicating CI definition can strongly influence study results.

3.3 Impacts of Cutting Intensity and Recovery Time

Cutting intensity had significant impacts on the relative change of DBH growth, stand BA, volume, and AGBC, the four variables with sufficient observations (Figs 1-2). Overall, the relative changes in DBH growth increased linearly with CI (r = 0.31, P<0.01) but with a large variation among individual studies (*SE*=79%), especially when RY< 5 years. In contrast, the relative changes decreased linearly in stand BA (r=-0.88, P<0.01) and volume (r=-0.67, P<0.01), with the largest slope and the most significant tendency in short term (RY< 5 years). The change pattern for the AGBC was similar to that of the two structural metrics (stand BA and volume) and exhibited a significantly decreased trend over the low-high CI gradient (r=-0.39, P<0.01) (Fig. 2).

The trend along the RY gradient reflects ecosystem recovery patterns after disturbance (Fig. 3). Overall, the magnitude of the relative changes induced by partial cutting reduced with the increasing of RY as shown by a decreasing trend in both the positive effects on DBH growth and the negative effects on BA, volume, and AGBC. The recovery or returning of these variables to uncut levels depended strongly on CI, and the recovery time was positively related to CI (Fig. 3).The recovering trends, indicated by the slopes of the regression, were statistically significant for stand BA ($P<0.01$), volume ($P<0.01$), and AGBC ($P<0.01$), but not for DBH growth ($P=0.43$). In addition, the trends of the ecosystem recovery varied with the CI for different variables. A statistically significant decreasing trend in the relative change of DBH growth was observed along RY under light cutting ($r=-0.25$, $P<0.05$), whereas the trends under moderate ($P=0.53$) and heavy cutting ($P=0.50$) were not significant. In contrast, the recovering trend in AGBC under light cutting was not significant ($P=0.63$) but those under moderate ($P<0.05$) and heavy ($P<0.01$) cuttings were significant. The relative changes in both stand BA and volume increased significantly as RY became longer under all CI groups.

General linear models (Gujarati, 1970) were developed to investigate whether the responses of forest to partial cutting can be predicted using the variables in the dataset (Table 3). Our linear models only explained a small fraction of the relative change of DBH growth, indicating some variables not included in this study may play a role. In contrast, the explanatory power of the models for the relative changes in stand BA, volume, and AGBC using CI and RY as independent variables were 43%, 48%, and 65%, respectively, and improved to 65%, 76%, and 76%, respectively, when adding three more independent variables (forest type, climatic zone, and CI definition). These results suggest the effects of partial cutting on a forest ecosystem can be mainly explained by CI and RY, but other factors (e.g., climate zone, forest type, and CI definition) contributed significantly as well.

4 Discussion

4.1 Forest Structure Change after Partial Cutting

Our synthesis indicates that partial cutting stimulates the growth of residual trees significantly, in spite of large variations among cutting intensity (i.e., CI), recovery years (i.e., RY), and site conditions, which corresponds to the general notion that partial cutting reduces individual competition and thus should have a positive effect on residual tree growth (Walter and Maguire, 2004; Vesala et al., 2005; Navarro et al., 2010). Overall, the relative changes of DBH growth correlated positively with the increase of CI, which was also comparable to many individual studies (Juodvalkis et al., 2005; Peña-Claros et al., 2008). Moreover, we found an overall declining trend of the positive impacts of partial cutting on DBH growth over time or along recovery years, indicating that the growth stimulation effect on residual trees should decline with ecosystem recovery over time, consistent with previous speculations (e.g., Sánchez-Humanes and Espelta, 2011). However, uncertainties remain in the changes of DBH growth after partial cutting. First, the relative changes in DBH growth correlated positively to CI and negatively to RY in general (Table 2), but the relative changes along the CI gradient in the short term (RY<5 years) (Fig 2) and along RY sequences after moderate and heavy cutting were not significant (Fig 3). Second, large variations were observed in the relative changes of DBH growth. This might suggest that other factors including cutting method, species, and site conditions may exert significant impacts on the magnitude of the relative changes of DBH growth after partial cutting (Skovsgaard, 2009). For example, we found that the DBH growth was more intensive in the broadleaf trees than in conifers compared with the uncut controls, and was lower in subtropical forests than the other forests, mainly because of the different levels of light improvement for remaining trees after cutting activities (Hale, 2003).

The relative changes in stand BA and volume following cutting varied significantly along the cutting intensity and recovery years gradients, with the greatest decrease in the short term under heavy cutting (Figs 2 and 3). This change pattern supports the hypothesis that the impact of partial cutting is relatively short-term with the greatest impacts in the early years after disturbance under heavy disturbance intensity (Amiro et al., 2010; Liu et al., 2011). The returning of stand BA and volume to uncut level depends strongly on cutting intensity with a longer time needed for a higher intensity (Figs 2 and 3). These results suggest that the impacts of partial cutting on forest structure decline over time owing to the forest recovery, and the magnitude of the recovery was closely related to the cutting intensity—both of them were consistent with previous understanding (Juodvalkis et al., 2005).

4.2 Carbon Stock Dynamics after Partial Cutting

One of the most crucial issues in studying ecological consequences of partial cutting in forest is how it impacts the carbon stocks over years under different disturbance intensities. A conceptual trajectory of C changes following a cutting is a large pulse of C loss as a result of the cutting followed by subsequent recovery over time (Liu et al., 2011; Weng et al., 2012; Goetz et al., 2012). The returning to pre-cutting levels can take decades and varies with CI (Pregitzer and Euskirchen, 2004). Our synthesis corresponds well to this trajectory and suggests that C storage in AGBC after partial cutting decreased linearly with CI (Fig. 2). At the same time, the carbon loss induced by partial cutting recovered with time (Fig. 3), which confirms that partial cutting may only have a short-term negative impact on carbon accumulation in vegetation (Vargas et al., 2009; Amiro et al., 2010). However, we did not find significant recover trends after low-intensity cutting in our compiled database, suggesting that low cutting effects may be outweighed by the other effects induced by the between-site variations, such as the differences in stand structure, forest type, and stand age (Ryan et al., 2004; Blanco et al., 2006). In addition, it will remain difficult to determine how much time is needed for a complete recovery since there were no observations on AGBC longer than 42 years in our synthesized database. Using the linear models, we estimated that the AGBC of a temperate deciduous forest requires an average of 31 years to return to the uncut level following partial cutting with a CI of 0.5 (defined by stand BA), and it requires 52 years to recover from clear-cutting (CI is 1). These predictions were comparable to the model study that suggested the period required to replace carbon lost during and after moderate cutting should be within 50 years and between 50 and 100 years for clear-cutting in ponderosa pine stands in Oregon (Law et al., 2001).

Understory C was stimulated significantly by partial cutting in all of the studies. This stimulation can be mainly attributed to an increase in the availability of light, water, and nutrients to understory because of tree removal (Aussenac, 2000; Kleintjes et al.,2004; Deal, 2007). However, the C increase in understory cannot compensate the C loss in AGBC since it only accounts for a substantially small proportion of the aboveground biomass in forest as a whole (Gilliam, 2007). In addition, understory would have impacts on residual tree growth through competition for moisture and nutrient.

Soil C stored in the forest floor reflects the balance between C input by litterfall, rhizodeposition and cutting residuals, and the C release during decomposition (Jandl et al., 2007). The removal of overstory trees reduces the annual litterfall input directly (Blanco et al., 2006; Campbell et al., 2009; Kunhamu et al., 2009), which is expected to exert certain negative impacts on the C stock in the forest floor since the accumulation of annul litterfall is an important component of forest floor C stock. At the same time, increase in soil surface temperature after partial cutting, which could accelerate the decay rates (Piene and van Cleve, 1978; Kunhamu et al., 2009), might also contribute to the reduction of the C stock on the forest floor. However, our synthesis indicates the change in the forest floor C stock was not significantly affected by cutting. This finding can be largely explained by the fact that the negative effects of decreased C input from litterfall together with the increase in the decomposition rate of the forest floor C may have been compensated by the immediate C input of cutting residues into the forest floor (de Wit and Kvindesland, 1999), and the following ecosystem recovery over time.

Our synthesis indicates that the change in mineral soil C after partial cutting was not significant, consistent with the findings from the two previous meta-analyses (Johnson and Curtis, 2001; Nave et al., 2010).The C stock in mineral soil varies greatly among sites and is primarily determined by other influences such as soil chemistry and physical characteristics (Nave et al., 2010).

It should be noted that the biomass C removed generally did not return immediately to the atmosphere but rather remained store in a durable status such as in wood products (Fahey et al., 2009), which (if long lived) can be considered a C sink (Pacala et al., 2007). The removed biomass was one major contributor to global energy supply (Berndes et al., 2003). Moreover, it’s widely accepted that partial cutting alters species composition and stand structure, which can provide many benefits, such as enhancement of wood products and reduction of fire risk (Kolb et al. 1998;Harvey et al., 2002; Frey et al., 2003; McDowell et al. 2006;Campbell et al. 2009). Thus, the immediate AGBC loss induced by partial cutting can be repaid in other terms of forest services and functions.

4.3 Implications and Challenges

It is evident that cutting practice significantly affects the structure and C stocks of the forest ecosystem. Because partial cutting will likely continue as a major type of silvicultural treatment and the demand for timber products continues to rise, forest management practices should be implemented in a way to reduce the negative impacts on forest functions and improve sustainability. Our meta-analysis confirms that C storage in the forest sector can be enhanced either by increasing the time between cutting activities to allow sufficient time for forests to recover, or reducing the CI during each cutting activity (Harmon et al., 2009). For instance, Øyen and Nilsen (2002) reported that the CI, defined by volume, should not be more than 65% in southeast Norway in order to keep the forest biomass sustainable, given a cutting cycle of less than 50 years. If managed sustainably, partial cutting could simultaneously preserve remaining native forests and function as a long-term carbon sink (Berthrong et al., 2009; Powers et al., 2012), and even increase C storage while providing as many forest products as the traditional clear-cutting (Harmon and Marks, 2002).

However, several challenges still preclude our comprehensive understanding of the dynamics in forest ecosystems affected by partial cutting. First, large geographic bias existed in the field observations we have assembled (Figs S1 and S3). About 63% of the case studies were from North America, but their forested area only accounts for 17 % of the world's total forest area (FAO, 2010). Comparatively, the number of studies was much lower in Africa and South America (Fig. S3). Second, the depth of the mineral soil was restricted to the surface soil with a depth of 0-15 cm in our database. However, it has been recognized that the relative change of carbon stock might be equally important in the subsoil (Don et al., 2011). Third, other factors such as cutting methods (Johnson et al., 2002; Blanc et al., 2009), post-treatment methods (Olsson and Staaf, 1995), stand age (Juodvalkis et al., 2005), and site conditions (Skovsgaard, 2009) also exerted significant impacts on the responses of forest ecosystems to partial cutting. However, because of the lack of detailed description of these variables in many studies in our database, their impacts could not be analyzed in this study. Forth, long-term experiments are rare and urgently needed. Many model studies suggested that partial cutting increased the ecosystem carbon in the long term (Garcia-Gonzalo et al., 2007; Taylor et al., 2008; Thiffault et al., 2011). However, it is still difficult to determine how long a complete recovery would take due to the lack of long-term experiments. Finally, the remote sensing techniques are a cost-effective way to detect large-scale changes in both forest area and carbon storage (Skole and Tucker, 1993; Achard et al., 2002). However, it is difficult to isolate the effects of partial cutting from the other disturbances using remote sensing (Houghton, 2005; Asner et al., 2005; Peres et al., 2006; Liu et al., 2011). For a better understanding of the consequences of partial cutting at regional or global scale, both the inventories and remotely sensed data sets may be needed (Goetz et al., 2012).

5 Summary

This study provides a comprehensive assessment of the dynamics of several key forest properties following partial cutting. Our results show that partial cutting decreases stand BA and volume greatly, but it can promote the growth of residual trees. Partial cutting reduces AGBC significantly while greatly increased C storage in the understory. The C stocks on forest floor and on mineral soil are not significantly affected by partial cutting.

For the four variables with sufficient observations (DBH growth, stand BA, volume, and AGBC), the magnitude of the relative change increases linearly with the CI and decreased linearly over time. It appears that CI and RY are the major factors responsible for the observed variations among various studies. Nevertheless, we found other factors (e.g., climate zone, forest type, and CI definition) also play a role. Results highlight the variable responses of the different structural characteristics and C stock components to partial cutting and the intrinsic nature of ecosystem resilience after the disturbance. Although partial cutting generally reduced C storage in aboveground biomass through removing individual trees from a forest, it can provide many benefits in other ways. Additionally, the data extracted from various studies did not enable us to determine how long it would take for a complete recovery under different CI levels. To further our understanding of the impacts of partial cutting, we recommend future efforts should be tailored to reduce the geographic bias of field studies and increase the depth of soil sampling and the duration of the experiments.

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Figure captions

Fig. 1 Overall directions and magnitudes of the relative changes (%) in the growth of diameter at breast height (DBH growth), stand basal area (BA), volume, aboveground biomass carbon (AGBC), understory C storage, forest floor C, and mineral soil C after partial cutting, compared to the uncut control. The error bars are the standard error (SE). The results of One-Way ANOVA ($P<0.05$) among three cutting intensity (CI) groups (light [L]: CI<34%; moderate [M]: 34%⩽CI< 67%; and heavy [H]: CI⩾67%) are shown beside the error bars, with a different letter meaning a difference significant at $P<0.05$. The values on the X-axis for DBH growth and understory C are 10 times those of other variables.

Fig. 2 The relative changes (%) along the CI gradient where the observations were grouped by the recovery years (RY) since cutting activities into short (green circle: RY≤5 years), medium (blue circle: 5 years <RY≤10 years), and long (red circle: RY>10 years) time periods. The dotted lines represent the linear fit curves of short, medium, and long RY with corresponding colors, and the bold black line indicates the linear fit curve of all observations. The correlation coefficient (R), confidence of significance (P), standard error (SE), and the number of observations (N) of each linear regression analysis are shown at the bottom of figure panel. Five observations that are larger than 400% were not shown in the figure panel of DBH growth.

Fig. 3 The relative changes (%) along the RY gradient, where the observations were grouped into L (green circle), M (blue circle), and H (red circle) cutting levels. The dotted lines represent the linear fit curves of the cutting under L, M, and H intensities with corresponding colors, and the bold black line indicates the linear fit curve of all cutting (All). The *R*, *P*, *SE* and *N* of each linear regression analysis are shown at the bottom of each figure panel. Five observations that are larger than 400% were not shown in the figure panel of DBH growth.

Fig. 4 Scatterplots of the mean relative changes (%) of DBH growth and stand BA for different forest types (i.e., broadleaf and coniferous) grouped by cutting intensity and recovery years when there are three or more observations for the group. C1 to C10 represents the cutting intensity levels ranging from 0-10 to 90-100 with 10 percent interval. Y1, Y2, and Y3 indicates the number of recovery years of 0-5, 5-10, and >10 yr., respectively.

Fig. 5 Scatterplots of the mean relative changes (%) of DBH growth and stand BA for different climatic zones (i.e., tropical, subtropical, Mediterranean, temperate marine, temperate continental, and boreal) grouped by cutting intensity and recovery years when there are three or more observations for the group.

Table 1 Mean values of the relative changes (%) for the seven variables related to forest structure and carbon (C) storage, grouped by cutting intensity (CI) classes if available.

Indicators	CI classes	Mean relative change (%) (lower and upper 95% bootstrapped confidence intervals)	Mean CI	Mean RY	Number of observations	Number of studies
DBH growth	Light	66.90 (46.57, 90.15)	0.19	12	65	15
	Moderate	101.99 (82.69, 121.26)	0.49	8	79	22
	Heavy	169.76 (120.23, 229.20)	0.83	14	64	12
	All	111.88 (92.15, 135.86)	0.50	11	208	31
Stand BA	Light	-15.18 (-18.16, -11.80)	0.24	9	98	24
	Moderate	-37.28 (-39.76, -34.81)	0.46	8	94	27
	Heavy	-68.31 (-72.58, -64.29)	0.80	10	46	13
	All	-34.18 (-37.36, -31.19)	0.45	9	238	35
Volume	Light	-20.76 (-25.07, -16.55)	0.22	10	50	12
	Moderate	-29.62 (-32.51, -26.71)	0.44	9	32	11
	Heavy	-62.57 (-67.06, -58.57)	0.76	11	10	4
	All	-28.39 (-32.01, -25.08)	0.36	10	92	15
AGBC	Light	-28.21 (-36.08, -20.31)	0.26	7	20	8
	Moderate	-42.16 (-46.39, -27.94)	0.53	5	48	18
	Heavy	-49.18 (-56.33, -41.97)	0.88	12	62	11
	All	-43.36 (-47.67, -39.33)	0.65	9	130	26
Understory C storage	All	391.54 (220.04, 603.82)	0.61	4	19	4
Forest floor C	All	**-9.24 (-23.35, 3.50)**	0.41	5	30	12
Mineral soil C	All	**-2.93(-9.45, 3.59)**	0.44	4	28	11

Significant transitions, inferred as approximate 95% bootstrapped confidence intervals (based on 1000 bootstrap samples) that contain 0, are in bold, which suggests the relative changes in the variable was insignificant compared to the uncut control.

DBH growth: growth of diameter at breast height; BA, basal area; AGBC, aboveground biomass C; RY: recovery years since cutting activities.

Table 2 Partial correlation coefficients between relative changes of the seven variables (related to forest structure and C storage) and potential driving factors.

Indicator	CI	RY	C_1	C_2	C_3	C_4	C_5	F_1	F_2	DCI_1	DCI_2	df
DBH growth	0.23**	-0.18*	-0.24**	0.33**	-0.01	-0.06	-0.15*	-	0.22**	0.23**	-0.28**	201
Stand BA	-0.64**	0.27**	-0.20**	-0.05	-0.05	0.35**	-0.16*	-0.16*	0.03	0.21**	-0.17**	238
Volume	-0.67**	0.26*	-	0.22*	0.09	-0.10	0.22*	-	-0.21	0.63**	-0.03	89
AGBC	-0.69**	0.77**	0.09	-0.06	-0.22*	0.37**	0.07	-	0.10	-0.08	0.36**	126
Understory C storage	0.60**	-0.12	-	-	-	-	-	-	-	-	-	-
Forest floor C	-0.07	-0.31	-	-	-	-	-	-	-	-	-	-
Mineral soil C	-0.06	-0.24	-	-	-	-	-	-	-	-	-	-

*. Correlation is significant at the 0.05 level (2-tailed); **. Correlation is significant at the 0.01 level (2-tailed). df is the degrees of freedom

C_1~C_5: dummy variables for climate zone where Tropical was considered the base climate zone. C_1 (=1 if is Subtropical, =0, otherwise), C_2 (=1 is Mediterranean, =0, otherwise), C_3 (=1 if is Temperate marine, =0, otherwise), C_4 (=1 if is Temperate continental, =0, otherwise), C_5 (=1 if is Boreal, =0, otherwise).

F_1~F_2: dummy variables for forest type where coniferous was taken as the base forest type. F_1 (=1 if lies in mixed group, =0, otherwise), F_2 (=1 if lies in broadleaf group, =0, otherwise).

DCI_1~DCI_2: dummy variables for the definition of cutting intensity where definition by stems number was considered the base definition.DCI_1 (=1 if defined by basal area, =0, otherwise), DCI_2 (=1 if defined by volume, =0, otherwise).

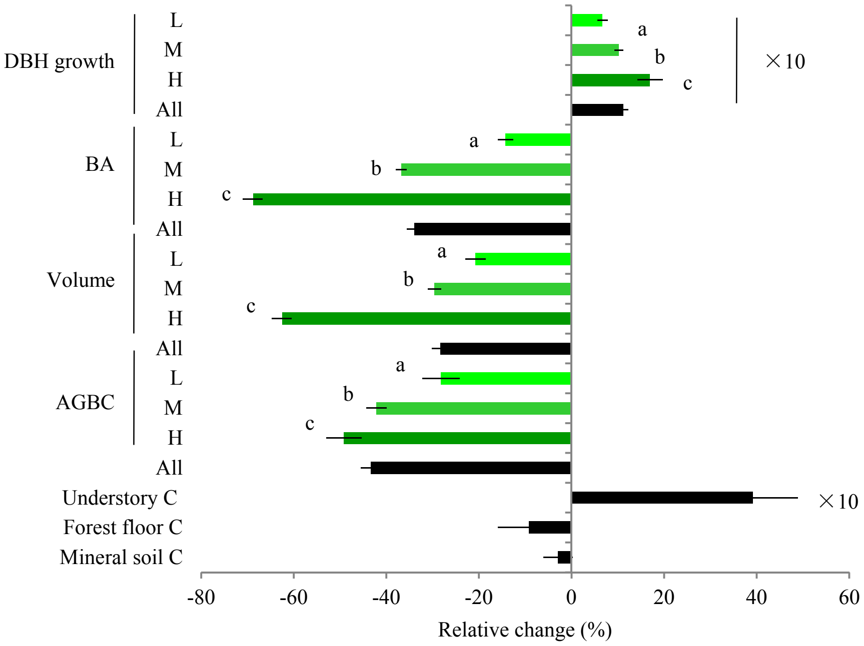
Table 3 General linear models of potential driving factors predicting the relative changes (%) for the four variables with sufficient observations (P<0.001)

Indicators	R^2	Liner model
DBH growth	0.13	$-1.90CI-1.73^{*}RY+112.87^{**}$
	0.29	$12.73CI-3.25^{**}RY-47.89C1+68.24^{*}C_2+49.18C_3+24.70C_4-43.82C_5+61.17^{**}F_2-15.71DCI_1-2.79DCI_2+84.47^{*}$
Stand BA	0.43	$-54.58^{**}CI+0.70^{**}RY-11.91^{**}$
	0.65	$-49.56^{**}CI+0.65^{**}RY-4.12C1-35.44^{**}C_2-22.93^{**}C_3-25.18^{**}C_4-36.72^{**}C_5-20.28^{**}F_1-2.51F_2+23.18^{**}DCI_1+17.83^{**}DCI_2-11.17^{*}$
Volume	0.48	$-62.26^{**}CI+0.44^{*}RY-10.63^{**}$
	0.76	$-91.85^{**}CI+0.87^{**}RY-2.79C1+15.85C_2-4.10C_3-25.18C_4+2.17C_5+1.73F_2+29.68^{**}DCI_1+25.51^{**}DCI_2-26.26^{*}$
AGBC	0.65	$-58.66CI^{**}+2.05Y^{**}-22.73^{**}$
	0.76	$-74.79^{**}CI+1.85^{**}RY+13.26C1+7.74C_2+8.85C_3+15.00^{**}C_4+20.17^{**}C_5+7.65^{**}F_2+3.98DCI_1+12.57^{*}DCI_2-33.41^{**}$

*. Correlation is significant at the 0.05 level (2-tailed); **. Correlation is significant at the 0.01 level (2-tailed)

The abbreviations are the same as Table 2.

Figure 1



DBH growth
BA
Volume
AGBC
L
M
H
All
Understory C
Forest floor C
Mineral soil C
a
b
c
×10
-80
-60
-40
-20
0
20
40
60
Relative change (%)

Figure 2

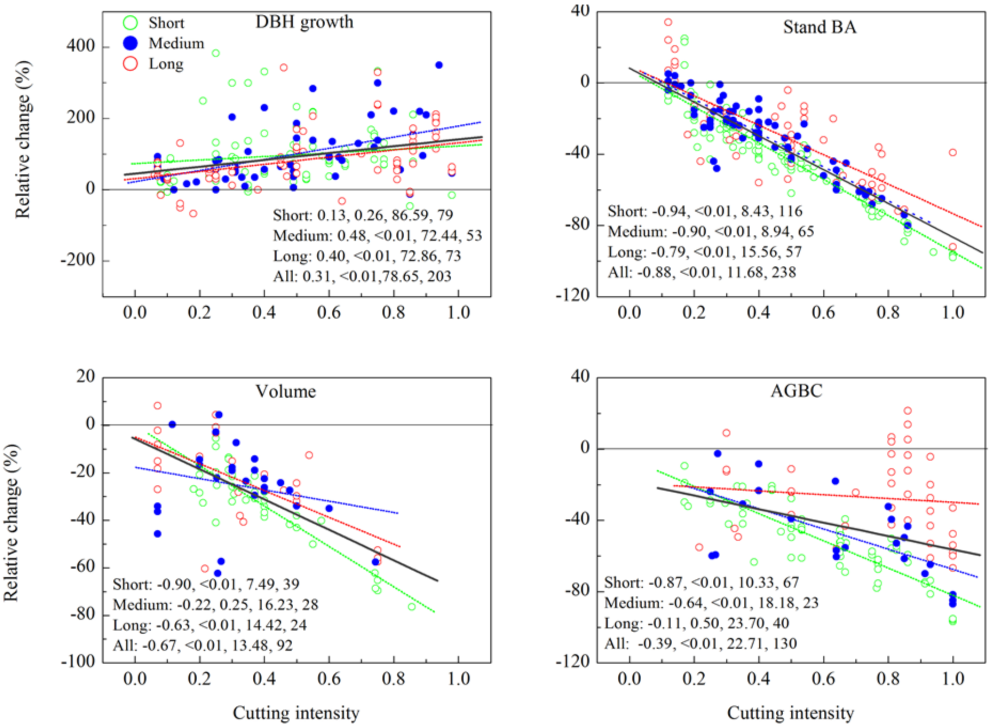
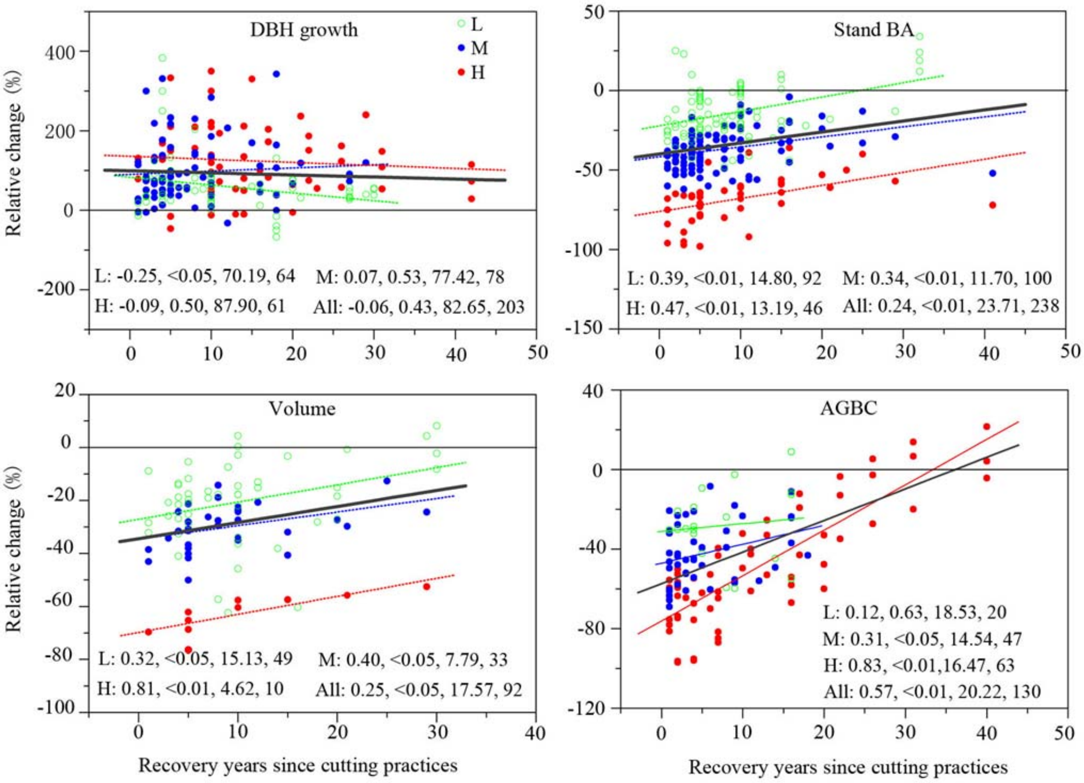
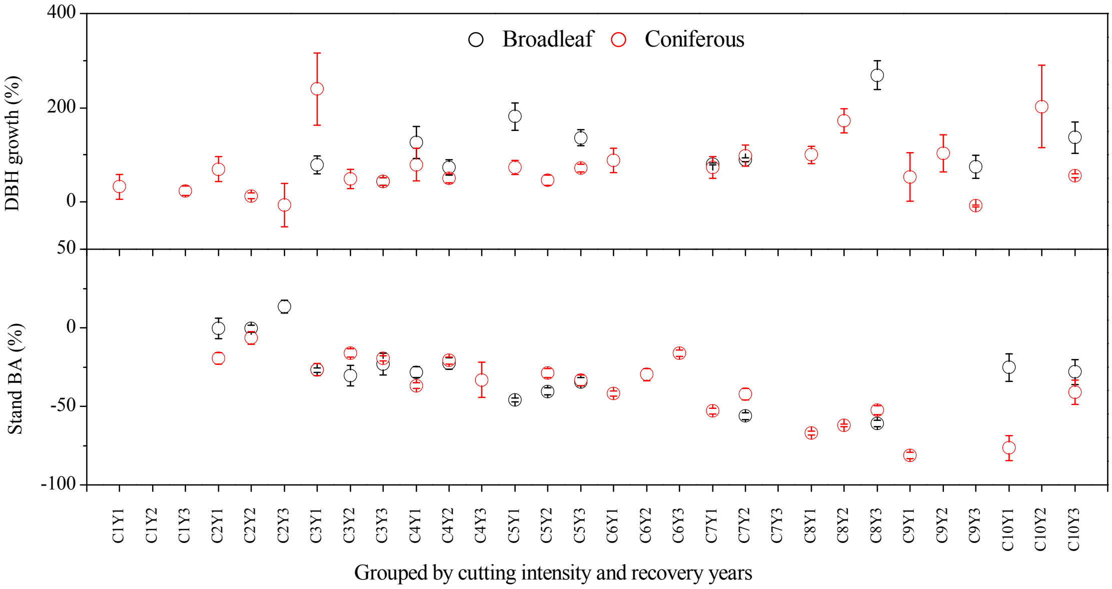

○ Short
● Medium
○ Long
DBH growth
Stand BA
Volume
AGBC
Relative change (%)
Cutting intensity
400
200
0
-200
40
0
-40
-80
-120
20
-20
-60
-100
0.0
0.2
0.4
0.6
0.8
1.0
Short: 0.13, 0.26, 86.59, 79
Medium: 0.48, <0.01, 72.44, 53
Long: 0.40, <0.01, 72.86, 73
All: 0.31, <0.01,78.65, 203
Short: -0.94, <0.01, 8.43, 116
Medium: -0.90, <0.01, 8.94, 65
Long: -0.79, <0.01, 15.56, 57
All: -0.88, <0.01, 11.68, 238
Short: -0.90, <0.01, 7.49, 39
Medium: -0.22, 0.25, 16.23, 28
Long: -0.63, <0.01, 14.42, 24
All: -0.67, <0.01, 13.48, 92
Short: -0.87, <0.01, 10.33, 67
Medium: -0.64, <0.01, 18.18, 23
Long: -0.11, 0.50, 23.70, 40
All: -0.39, <0.01, 22.71, 130

Figure 3


DBH growth
L
M
H
Relative change (%)
400
200
0
-200
L: -0.25, <0.05, 70.19, 64
M: 0.07, 0.53, 77.42, 78
H: -0.09, 0.50, 87.90, 61
All: -0.06, 0.43, 82.65, 203
0
10
20
30
40
50
Stand BA
50
0
-50
-100
-150
L: 0.39, <0.01, 14.80, 92
M: 0.34, <0.01, 11.70, 100
H: 0.47, <0.01, 13.19, 46
All: 0.24, <0.01, 23.71, 238
0
10
20
30
40
50
Volume
Relative change (%)
20
0
-20
-40
-60
-80
-100
L: 0.32, <0.05, 15.13, 49
M: 0.40, <0.05, 7.79, 33
H: 0.81, <0.01, 4.62, 10
All: 0.25, <0.05, 17.57, 92
0
10
20
30
40
Recovery years since cutting practices
AGBC
40
0
-40
-80
-120
L: 0.12, 0.63, 18.53, 20
M: 0.31, <0.05, 14.54, 47
H: 0.83, <0.01,16.47, 63
All: 0.57, <0.01, 20.22, 130
0
10
20
30
40
50
Recovery years since cutting practices

716 **Figure 4**

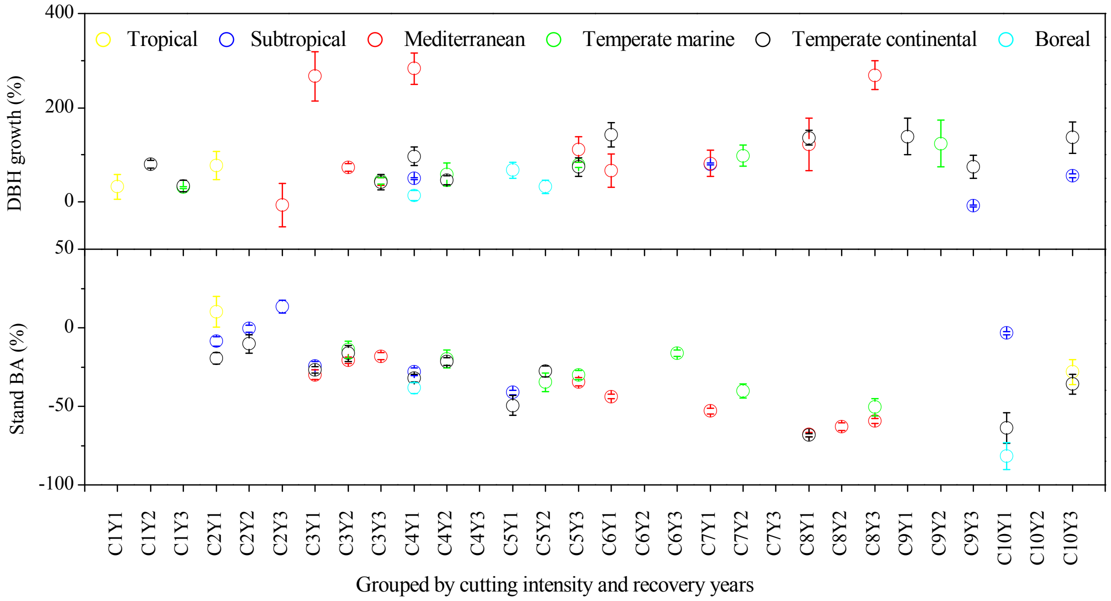


717

718

719

720 **Figure 5**



721

722