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Decline in Aboveground Biomass Due to Fragmentation in Subtropical Forests of China

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Abstract: Fragmentation has long been considered the primary cause for ecosystem degradation and biodiversity loss worldwide. Forest fragmentation affects ecosystem functioning and biodiversity in multiple ways. Here, we ask how forest fragmentation influences aboveground biomass storage (AGB) in sub-tropical forests in China. We established 207 20 m × 20 m plots within 69 forest fragments of varying size. Forest fragmentation process simulation was carried out via repeated quadrat sampling using different sized quadrats in two non-fragmented stands. AGB was estimated and compared across forest fragments and quadrats with different sizes within two non-fragmented stands. Our results indicate that AGB is significantly lower in forest fragments than in quadrats within two non-fragmented forests. In addition, species richness and abundance were lower in fragmented stands, respectively. In fragmented forests, the average diameter at breast height (DBH) increased with decreasing patch size, while declined for non-fragmented plots. Species richness, abundance, and mean DBH have strongly positive effects on AGB. This was the case both in forest fragments and quadrats within two non-fragmented forests. Forest fragmentation leads to lower richness, lower abundance, and higher mean DBH in forest fragments than in the two non-fragmented forests. Our results suggest that forest fragmentation increases edge habitats, which drastically decreases forests aboveground biomass storage. These results show that land degradation not only reduces the area of forests, but also reduces the aboveground biomass carbon density of forests.

Keywords: forest fragmentation; patch size; edge effects; aboveground biomass; fengshui forests

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1. Introduction

Land use changes are one of the strongest drivers of habitat loss, ecosystem shifts and biodiversity changes, especially in sub-tropical forest regions [1,2]. However, forest fragmentation is widespread across the globe, resulting in increased carbon emissions and a loss of sequestration potential [1,3]. The loss, fragmentation, and disturbance of forests thus represent a major threat to biodiversity and ecosystem services, including carbon storage and climate regulation [4–6]. Furthermore, forest fragmentation contributes between 6% to 17% of global anthropogenic CO_2 emissions to the atmosphere [7,8]. However, large uncertainties in emission estimates arise from inadequate data on carbon storage in forests and on the regional rates of deforestation [9].

Habitat fragmentation is particularly problematic in sub-tropical forests [10]. Fragmentation in these ecosystems arises due to various types of human-caused disturbance [9,11], such as logging, grazing, and fire disturbances [12]. While deforestation has many clear negative impacts on carbon storage, there is considerable uncertainty surrounding the carbon dynamics within fragmented sub-tropical forests [10,13].

The impacts of forest fragmentation on the structure and composition of forest communities can be complex. Forest fragmentation leads to multiple disparate forest patches of differing sizes and isolation [7]. Forest fragmentation can often result in new forest edge areas being created [14–16]. The forest edge is the interface between fragments and their adjoining clearings, and the proliferation of edge habitat has major impacts on multiple ecological processes. Edge effects are among the primary mechanism by which forest fragmentation can influence biodiversity and ecosystem processes and clearly play a dominant role in biomass dynamics in fragmented forests [4,15,17]. Biomass decline along forest edges may even be an important source of atmospheric carbon [18]. Fragmentation of natural forests not only removes carbon stocks, but also has a long-term impact on remnant forest fragments through changes in the abiotic and biotic environments [8]. Newly created edge habitats are characterized by elevated temperatures, reduced humidity, and increased sunlight [9,19,20]. Likewise, vapor pressure deficits can penetrate at least 40–60 m into fragment interiors [21]. Recent studies have suggested that fragmentation also alters forest dynamics, causing sharply elevated rates of tree mortality, which resulted in significant biomass loss near forest edges [22]. This is likely a result of microclimatic changes and increased wind turbulence near forest edges [23]. However, relatively few studies have quantified these mechanisms in sub-tropical regions [24,25].

AGB in both pristine evergreen and fragmented forests have been studied for long time [26–29]. However, the effects of forest fragmentation on AGB potential are still not completely understood. Moreover, while it has been well documented that fragmentation can reduce AGB, our understanding of how compositional shifts caused by fragmentation translate to changes in AGB potential of tree communities remains unclear, especially in subtropical forests. More research is thus needed to understand how forest fragmentation limits AGB capacity. In this study, we compared AGB and community characteristics (abundance, richness, and mean DBH) in fragmented forests and non-fragmented sub-tropical forests of South China. We hypothesized that: (1) forest fragmentation reduced AGB compared to non-fragmented forests; and (2) loss of AGB in fragmented forests is due to species richness declines.

2. Materials and Methods

The study was conducted within the heterogeneous, fragmented, and human-dominated landscape of Guangzhou, Guangdong Province, South China. Guangzhou lies between 22°26′ and 23°56′ N, and 112°57′ and 114°03′ E (Figure 1). The region has a sub-tropical monsoon climate. The annual mean temperature is 21.8 °C and the annual precipitation is 1690 mm [30]. There is a pronounced wet season, with 75% of annual rainfall occurring between March and September. Typhoons and thunderstorms occasionally damage trees in the region, and the mild climate permits non-fragmented vegetation growth throughout the year. In near rural areas of Guangzhou there are 69 old-growth sub-tropical forest fragments, called fengshui forests. These forest fragments were surrounded by agricultural land and protected by local villagers. The elevation of these fragments varies from 21 m to 148 m a.s.l. These forests have retained many features of the original undisturbed vegetation of the region [27,31]. These landscapes thus offer an interesting opportunity to examine the potential effects of habitat loss and fragmentation on AGB.

We analyzed data from two stem-mapped plots belonging to the Center for Tropical Forest Science (CTFS) global plot network (http://forestgeo.si.edu/ (accessed on 11 May 2021)). The two CTFS plots (Dinghu plot and Heishiding plot) were used to estimate AGB from non-fragmented forests. The Dinghushan Nature Reserve located in the western section of Guangdong Province. It covers 1133 ha and is characterized by a sub-tropical monsoon climate with a mean annual temperature of 20.9 °C. The reserve is covered by sub-tropical and tropical monsoon evergreen broadleaved forests. The forest age is about 400 years. Dominants tree species in Dinghushan Nature Reserve are *Castanopsis chinensis*, *Schima superba, Engelhardtia roxburghiana*. In 2005, a 400 m × 500 m forest plot called the Dinghu plot was established within the core zone of the reserve so as to avoid intense human disturbances. All free-standing trees of at least 1 cm in diameter at breast height (DBH; 1.3 m aboveground) were tagged, measured, and identified to the species level, and their geographic coordinates were recorded following Condit [32]. The 20-ha plot includes 71,617 individual trees and shrubs belonging to 195 species, 119 genera, and 56 families. Mean annual precipitation is 1929 mm. The elevation of the plot varies from 230 m to 470 m a.s.l [33].

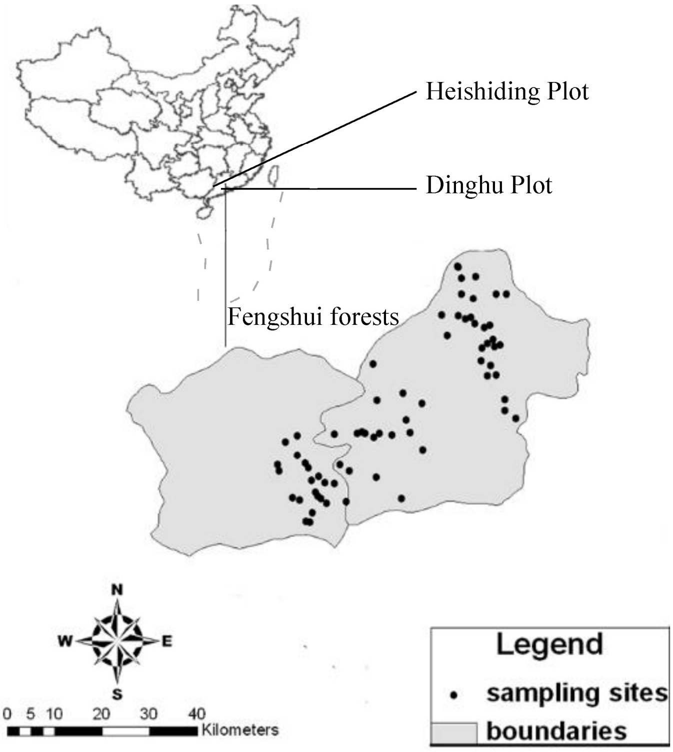


Figure 1. Location of study areas in South China.

We also used data from a 500 m × 1000 m plot in the Heishiding Provincial Reserve in western Guangdong province that was established in 2011 with the first census completed in 2013. The floristic composition of the forest is transitional between subtropical and tropical forests. The forest age is about 200 years. Dominants tree species in Heishiding Nature Reserve are *Cryptocarya concinna, Neolitsea phanerophlebia, Litsea acuminate*. The 50-ha plot includes 273,000 individual trees and shrubs belonging to 245 species, 160 genera, and 71 families. The average annual rainfall is about 1744 mm, with 79% of the annual rain falling between April and September. The mean maximum temperature is 19.6 °C and the elevation of the plot varies from 435.4 m to 698.4 m above sea level [34].

We selected 69 fragmented forests for sampling based on the following criteria: relatively well protected areas that were distributed within the same altitudinal range and had similar rainfall and temperature regimes [30]. Forest fragments varied in size from 3 ha to 41.3 ha. The forest age is about 100–150 years. Dominants tree species in these forest fragments are *Castanopsis chinensis, Schima superba, Endospermum chinense, Michelia chapensis*. First, we divided each forest patch into three parts (edge area, middle area, and interior area) based on the radius of the largest circle (Figure 2). Within each patch, we established three 20 m × 20 m quadrats that were used for vegetation sampling. One quadrat was placed in the approximate center of the fragment (interior quadrat), one was located in the center of edge area (edge quadrat), and one was placed in the middle area (middle quadrat). All standing trees (DBH ≥ 1 cm) were measured within each sampling quadrat.

Mean DBH and abundance were then measured for each quadrat. In addition, mean DBH and abundance of each forest fragment were estimated through weighted mean method based on the results of three different type of quadrats (interior, middle, and edge quadrats) within this fragment and the area of each fragment. We also calculated species richness for each forest fragment. Species' identification were made by experienced field botanists from the South China Botanical Garden, of the Chinese Academy of Sciences [35].

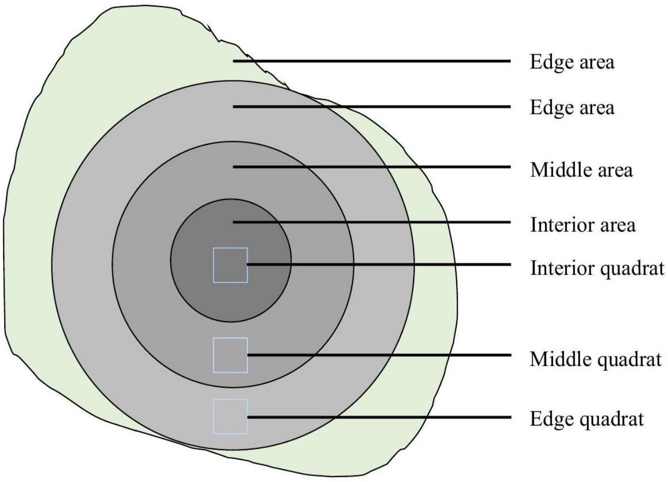


Figure 2. Schematic diagram of the quadrat sampling within 69 forest fragments.

AGB was estimated using allometric equations developed by Wen [36] for mixed forests in the Dinghushan Nature Reserve:

$$AGB = a \times DBH\hat{\ }b \tag{1}$$

where, a and b are statistical parameters (see Appendix A for equations and summary statistics). AGB of each stem was calculated as the sum of the dry weight of trunks, branches, and leaves. Then, AGB of each quadrat was calculated as the sum of AGB of all stems within this quadrat (Mg/ha). Finally, we estimated the AGB of each forest fragment using a weighted mean method based on the results of AGB within three different type of quadrats (interior, middle, and edge quadrats) within this fragment and the area of each fragment.

Finally, AGB of each stem within both the Dinghu and Heishiding plots were calculated according to the same allometric equations described above. In the present study, we simulated the process of forest fragmentation using the method of repeated quadrat sampling with different quadrat sizes within Dinghu plot and Heishiding plot [34]. These data sets are suitable because (1) our analysis is independent of spatial scale, (2) the plots contain similar climatic conditions to those found in the fengshui forests fragments. We obtained the modeling curves as follows: (1) we gridded the plot into quadrat of some maximum size (for example 1000 m × 500 m), down to the minimum quadrat size (for example 5 m × 5 m); (2) count the species richness and the number of all individuals in each quadrat; calculate the mean DBH of all stem in each quadrat; sum the AGB of all stems within each quadrat; (3) construct four curves (species richness-quadrat size, number of individual-quadrat size, mean DBH-quadrat size, and AGB-quadrat size) by repeating steps 1–2, decreasing quadrat size from 1000 m × 500 m, 995 m × 495 m, 990 m × 490 m, etc. down to the minimum quadrat 5 m × 5 m for 999 times [34].

Differences in AGB, species richness, abundance, and mean DBH within different sized quadrats sampled in the CTFS plots and sixty-nine forest fragments were analyzed via one-way analysis of variance (ANOVA). One-way ANOVA was also used to test the differences in AGB density within different types of quadrats (interior, middle, and edge quadrats). Linear models (LM) were used to test the effects of patch size on AGB, richness, abundance, and mean DBH. Generalized linear models (GLM) were used to assess the contributions of richness, abundance, mean DBH, patch size, and fragmentation (binary variable with two levels) to AGB in the forest communities. For all of the explanatory variables except fragmentation, values were standardized by subtracting the mean value of the variables and dividing by the standard deviation. This allows for a direct comparison of the relative importance of these explanatory variables.

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \beta_3 x_{3i} + \ldots + \varepsilon^i \ (i = 1,2, \ldots n) \tag{2}$$

where y_i is response variable (aboveground biomass); β_0 is an intercept, β_1, β_2, and β_3 were vectors of model coefficients; x_{1i}, x_{2i}, and x_{3i} were predictor variables. Here, the ε^i were drawn from a random variable E, that was gaussian distributed with a mean of zero and variance of σ^2, i.e., E~Normal (0, σ^2). The link function was "identity". In order to select the best-fit models, stepwise multiple regression was used. All statistical analyses were carried out in R version 3.1.2. Packages of "graphics", "stats", and "vegan" were used in the present study [37].

3. Results

3.1. Structure and Composition of Forest Fragments and Continuous Forests

Abundance and richness were significantly ($p < 0.05$) greater in interior and middle quadrats than in edge quadrats in 69 forest fragments. The proportion of shade-tolerant species was also significantly ($p < 0.05$) higher in interior quadrats versus edge quadrats, while, in contrast, the proportion of light-demanding species were significantly ($p < 0.05$) higher in edge quadrats than in interior quadrats. In addition, richness and abundance were significantly lower while mean DBH was higher in forest fragments than in the Dinghu plot and Heishiding plot, respectively, when the patch size of fragments is the same as that of quadrat size within non-fragmented forests (Table 1, Figure 3). Richness and abundance decreased while mean DBH increased with decreasing patch size in forest fragments (Table 2). A similar trend was observed for the two non-fragmented forests as well (Table 2).

Table 1. One-way ANOVA comparing community attributes between forest fragments and the two stem-mapped forests.

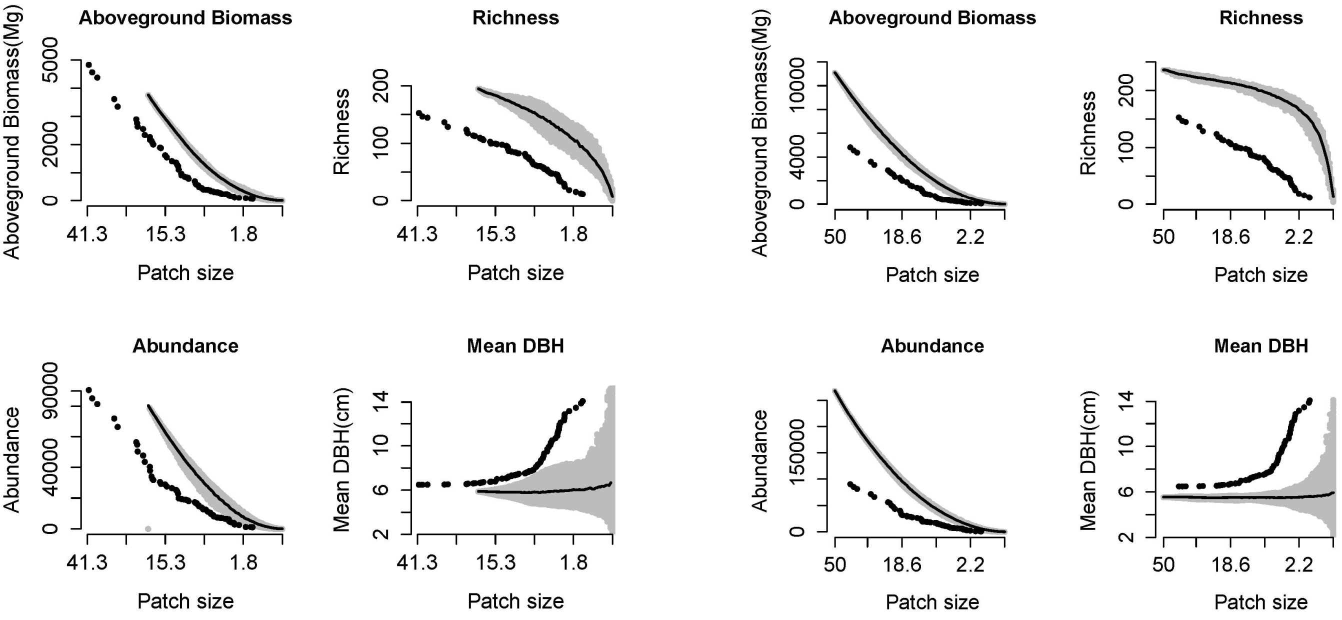
Variables	Fragments-Dinghu Plot		Fragments-Heishiding Plot	
	F Value	Sig [1].	*F* Value	Sig.
Biomass	21.2	***	41.39	***
Richness	186.4	***	313.1	***
Abundance	27.0	***	45.57	***
Mean DBH	140.5	***	195.7	***

[1] 0.1 > p > 0.05; *** $p \leq 0.001$.

Table 2. Summary of linear models analyses of impact of patch sizes' effects.

Variables	Fragments		Dinghu Plot		Heishiding Plot	
	Est. Coef.	Sig [1].	Est. Coef.	Sig [1].	Est. Coef.	Sig [1].
Biomass	124.35	***	189.64	***	224.16	***
Richness	3.46	***	7.08	***	2.21	***
Abundance	2235.52	***	4069.36	***	5302.61	***
Mean DBH	−0.17	***	−0.02	***	−0.001	**

[1] 0.1 > p > 0.05; ** 0.01 > p > 0.001; *** $p \leq 0.001$.



(**a**) (**b**)

Figure 3. Relationships between aboveground biomass, richness, abundance, and mean DBH with patch size (ha) in sixty-nine forest fragments (black dots) and quadrat size (ha). Grey dots were values of repeated quadrat sampling using different sized quadrats. Lines were mean value of grey dots: (**a**) Dinghu Plot; (**b**) Heishiding Plot.

3.2. Abovegrond Biomass Density of Forest Fragments

Aboveground biomass density was significantly higher in interior and middle quadrats than in edge quadrats within 69 forest fragments ($p < 0.001$; $p < 0.001$), respectively. AGB density in interior and middle quadrats were similar within larger forest patches (>10.1 ha). Rapid declines in AGB density within interior and middle quadrats were found at 7 ha and 4.7 ha, respectively, when patch size decreasing. AGB density was similar in middle and edge quadrats within smaller forest patches (<3.3 ha) due to these two types of quadrats were so close and sharing similar community characteristics (Figure 4).

3.3. Aboveground Biomass of Continuous Forests and Its Drivers

AGB was significantly lower in forest fragments than in the Dinghu plot and Heishiding plot, respectively, when the patch size of fragments is the same as that of quadrat size within non-fragmented forests (Table 1). In addition, AGB decreased with decreasing patch size both in forest fragments and in two non-fragmented forests as well (Table 2). All variables except fragmentation had positive effects on AGB (Table 3). Of these variables, abundance had the strongest impact on AGB, with more stems having an increased probability of AGB. In addition, we found evidence that AGB was influenced by fragmentation that was consistent with the above results (Tables 2 and 3).

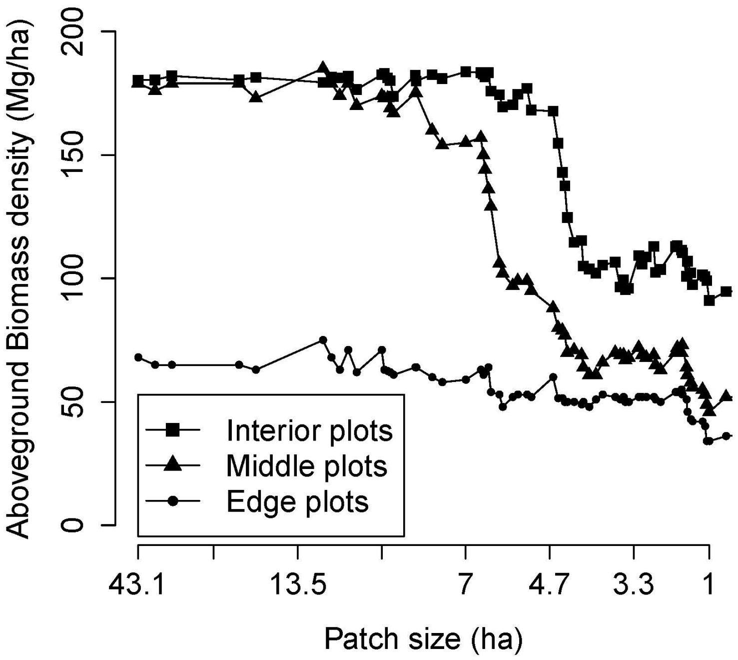


Figure 4. Edge effects on aboveground biomass density in sixty-nine forest fragments.

Table 3. Summary of generalized linear models analyses of aboveground biomass.

Variables	Est. Coef.	Std. Err.	Sig [1].
Intercept	−0.08	0.009	***
Richness	0.029	0.004	***
Abundance	0.723	0.010	***
Mean DBH	0.026	0.004	***
Patch size	0.262	0.010	***
Fragmentation	−0.115	0.012	***

[1] $0.1 > p > 0.05$; *** $p \leq 0.001$.

4. Discussion

Despite an extensive body of research on forest fragmentation, relatively few studies have focused specifically on the ways in which forest fragmentation can alter the link between community characteristics and ecosystem functions within sub-tropical forests. In the present study, we compared AGB loss and its determinants between forest fragments and non-fragmented forests. Our analysis shows that ecological changes within forest fragments magnify AGB loss (Tables 2 and 3). Our findings thus contribute to our understanding of the role vegetation plays in the global carbon cycle.

In the absence of significant disturbance, non-fragmented forests likely act as carbon sinks according to previous studies [7,20,28]. In contrast, fragmented forests likely contribute to carbon loss to the atmosphere [38]. Fragmentation affects AGB in forests, with potentially important implications for carbon storage and greenhouse gas emissions [8]. In this study, we evaluated differences in AGB and its drivers between fragmented and non-fragmented forests. Our results thus suggest that fragmentation drastically decreases AGB storage in forests. Sub-tropical forest fragments in south China had been found to experience a reduction in AGB compared to non-fragmented forests [27]. Forest fragmentation is one of the primary ways that human activity has altered biodiversity and ecosystem processes. Fragmented forest landscapes are becoming increasingly common in many parts of the world [20]. In addition, AGB significantly decreased when patch size decreasing (Table 3). However, it is likely that patch size is not a direct cause of the decline in AGB. Our results indicate a decline in AGB in smaller forest fragments (Tables 2 and 3, Figure 3), providing support for the hypothesis (1).

While the outcomes of forest fragmentation take many forms, one of the primary mechanisms by which fragmentation can change the diversity and function of a forest landscape is through edge effects [23]. The proliferation of forest edge habitats thus has major impacts on many ecological processes [3]. In this study, we found that the loss of biomass near edges in forest fragments agrees with other studies [12,18,23]. Furthermore, lower AGB in fragments than in simulation results showed that forest edge was the major factor limiting AGB in forest fragments (Table 1). In addition, the impact of edge effects on AGB may be greater in smaller fragments due to higher proportion of forest edge areas [30].

The community characteristics in forest fragments changed compared to non-fragmented forests, which is influenced by direct and indirect effects related to the habitat fragmentation process, edge effects, micro- and macroclimate, edaphic factors, biological interactions, population collapses from demographic or genetic events, changes in dispersal and pollination mechanisms and invasions by exotic species [39–41].

In this study, lower richness was found when patch size of forest fragments and quadrat size within two non-fragmented forests decreased (Table 2). Fragmentation results in loss of tree species. Lower richness was also found in edge quadrats. Previous works have shown that the collapse of shade-tolerant trees at forest edge is not typically counteracted by recruitments [4,42]. These changes are typified by the replacement of interior forest species with edge-tolerant generalist species and exotics [20,43]. Empirical studies also show that edges have a lower proportion of large-seeded and vertebrate-dispersed trees [44]. Habitat loss and fragmentation are probably the greatest threats to sub-tropical biodiversity through their alteration of many ecosystem functions [10]. AGB losses may be brought about by changes in habitat structure and tree species composition [45].

The relationship between species richness and ecosystem function is of long-standing theoretical and practical interest in ecology [31,46]. Results of this study showed that richness had positive effect on AGB both in fragmented and non-fragmented forests (Tables 2 and 3). Chisholm et al. [29] found that at very small spatial grains, species richness was generally positively related to biomass within plots. Specifically, they found that a doubling of species richness corresponded to a 53% increase in biomass. Indeed, species-rich stands had higher AGB than stands with lower richness. Our AGB estimates for species-rich sub-tropical forests in south China are closer to previous estimation from India [13]. Based on our simulations, we found these differences in species richness likely driving the declines in AGB due to fragmentation. Some hypotheses regarding how edge habitat affects AGB have been proposed, suggesting that AGB at the forest edge will decrease due to increased mortality and compositional shifts towards smaller, lower wood density species [15,23].

The shifts in tree community and structure caused by edge effects can have a significant effect on the ecosystem processes occurring in forest fragments [6]. After forest fragmentation, the forest edge structure might be affected, subsequently altering ecosystem processes. Higher mean DBH in forest fragments than in quadrats within two non-fragmented forests, suggests that forest fragments were affected by edge effects (Figure 3, Table 1). Emergent trees store a large portion of the AGB and contribute disproportionately to ecological services such as nutrient cycling, water catchment, soil erosion control, biodiversity retention, and provisioning of forest products [47,48]. In contrast to other forest fragments outside of China where large trees are uncommon, our study site is unusual in that large trees are nearly as abundant in fragments as they are in contiguous forests [31]. While these large trees buffer carbon loss in fragments, the resultant concentration of carbon within a smaller number of individuals is likely to have undesirable consequences for long-term carbon storage. Any impacts on larger trees, either by global change or other disturbances that affect their abundance and persistence, are therefore likely to have a major impact on forest AGB. Large trees over 40 cm DBH stored 31% of the total carbon in fragments, but only 26.1% and 24.2% in contiguous forests according to our former study [31]. However, lower AGB was found in forest fragments due to lower abundance of lager trees in the present study (Tables 1 and 2). In the present study, we expected that AGB storage in fragments would be highly sensitive to the loss of a small number of large individuals. The sharp loss in biomass observed in the forest fragments during fragmentation in the present study is in line with previous studies showing that the loss of large trees is characteristic of edge habitats [4]. Previous studies revealed that habitat fragmentation fundamentally alters the distribution of AGB in sub-tropical forests [33]. Fragments thus have reduced AGB storage compared to contiguous forests, particularly along fragment edges [45].

In a 32-year study of Amazonian forest edge habitats suggested that increased tree mortality was found within the first 100 m from the forest edge which can be one of the most important processes driving changes in species abundance and forest structure in forest fragments [14]. Near forest edges, frequent canopy disturbances increase the amount of light reaching the understory, which results in higher recruitment rates, higher densities of small trees, and higher liana densities [49,50]. Microclimate is significantly altered along a transition zone between adjacent ecosystems [24,51]. Along exposed forest patch edges, light and wind can penetrate beneath closed canopies, causing abrupt changes in temperature, moisture, and vapor pressure deficit [52]. The smaller the forest patch, the larger the proportion of the forest's interior area is influenced by edge-induced microclimates. However, the variation in patterns among microclimate variables highlight the fact that different aspects of microclimate vary in their patterns of forest influence, as has been noted in previous studies [24]. The results of this study will increase our understanding of the process of forest fragmentation and will also contribute to global research on AGB loss due to forest fragmentation.

Abiotic variables associated with edge habitats can explain the loss of tree biomass storage. For example, increased wind speeds at forest edges can extend up to 400 m into the forest interior, causing biomass loss and posterior mortality due to physical damage to trees [9,19]. The decrease in humidity and increase in air temperature resulting from edge formation could also have contributed to the overall reductions in tree biomass storage observed. For example, drought and high temperatures are related to biomass reductions due to enhanced tree mortality and changes in tree species composition [49,53]. Although forest fragments are usually well protected, they are minimally disturbed by nearby villagers for wood materials to be used as fuels and their livestock may feed on the plants in the fragments [54,55]. Therefore, stem density in the fragments would be reduced, especially the understory layer. In addition, reduced stem density and edge effects could accelerate the growth of trees in the fragments [56,57].

5. Conclusions

Here, we estimated AGB in sixty-nine forest fragments of varying sizes and compared them to estimates from two non-fragmented sub-tropical forests of southern China. By comparing estimates of AGB from field-based measurements to those from the results of forest fragmentation process simulation in two non-fragmented forests, we found that AGB in forest fragments was lower than in non-fragmented forests. In addition, AGB declined both in fragments and two non-fragmented forests as patch size or quadrat size decreased. Community characteristics (i.e., abundance, richness, and mean DBH) significantly determined AGB, and were influenced by edge effects created by forest fragmentation. Forest fragmentation increases AGB loss due to reduced richness and abundance. In conclusion, forest fragmentation and edge effects decrease storage of AGB in forest fragments through lower abundance, lower richness, and smaller patch sizes. A better understanding of the effects of forest fragmentation on AGB can provide a better picture of how alterations in forest structure and composition due to fragmentation may alter global carbon cycle. Results of the present study show that land degradation not only reduces the area of forests, but also reduces the aboveground biomass carbon density of forests. Furthermore, it will contribute to better evaluating the role of these forest fragments in regional carbon pools and provide data for developing and validating carbon cycling models for subtropical forests.

Author Contributions: Conceptualization, L.M.; methodology, L.M.; software, C.S.; validation, N.S., S.F.; formal analysis, W.Y.; investigation, C.S.; resources, W.Y.; data curation, D.G.; writing—original draft preparation, C.S.; writing—review and editing, L.M.; visualization, S.F.; supervision, D.G.; project administration, L.M.; funding acquisition, L.M. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data the materials that support the findings of this study are availability from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table 1. Allometric regression equations and summary statistics.

DBH-Class	Equations	Adjusted R^2	Standard Error of the Mean	*R.* Error (%)
DBH ≤ 5 cm	$WT = 0.05549 \times D^{2.87776}$	0.91164	0.60826	−0.23
	$WB = 0.01124 \times D^{3.16237}$	0.81933	0.30284	0.00
	$WL = 0.01551 \times D^{2.32693}$	0.86555	0.08602	0.42
	$WR = 0.02838 \times D^{2.65348}$	0.90495	0.22077	−0.27
5 < DBH ≤ 10 cm	$WT = 0.11701 \times D^{2.36933}$	0.88428	2.05700	0.04
	$WB = 0.01621 \times D^{2.93859}$	0.76490	1.79321	0.63
	$WL = 0.04169 \times D^{1.90082}$	0.68922	0.44047	0.39
	$WR = 0.04977 \times D^{2.19517}$	0.95730	0.32819	−0.16
10 < DBH ≤ 20 cm	$WT = 0.10769 \times D^{2.34891}$	0.77761	4.15734	4.55
	$WB = 0.00385 \times D^{3.15093}$	0.88184	3.81171	3.69
	$WL = 0.00372 \times D^{2.65113}$	0.82848	0.96151	0.57
	$WR = 0.03538 \times D^{2.29567}$	0.81687	3.46518	0.45
DBH > 20 cm	$WT = 0.03541 \times D^{2.65146}$	0.97844	36.71034	−2.34
	$WB = 0.00583 \times D^{2.94383}$	0.85965	52.85291	−1.61
	$WL = 0.07709 \times D^{1.55399}$	0.71000	4.94167	−0.30
	$WR = 0.01128 \times D^{2.67850}$	0.92962	24.5010	−1.11

WT = weight of trunk, WB = weight of branch, WL = weight of leaf, WR = weight of root.

These equations were used for estimating biomass of trunk, branch, leaf and root of each stem of different diameter at breast height. These equations were developed by Wen et al. (1997) [36] using total harvest method at Dinghushan Nature Reserve.

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