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Carbon emissions from land cover change in Central Vietnam

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ABSTRACT

The carbon emissions and removals due to land cover changes between 2001 and 2010 in the Vu Gia Thu Bon River Basin, Central Vietnam, were estimated using Landsat satellite images and 3083 forest inventory plots. The net emissions from above- and belowground vegetation biomass were equal to 1.76 $\pm$ 0.12 Tg CO_2, about 1.1% of the existing stocks. The vast majority of carbon emissions were due to forest loss, with the conversion of forest to cropland accounting for 67% of net emissions. Forest regrowth had a substantial impact on net carbon changes, removing 22% of emissions from deforestation. Most deforestation occurred in regrowth forest (60%) and plantations (29%), characterized by low carbon stock density. Thus identifying the type of forest where deforestation occurred and using local field data were critical with net emissions being 4 times larger when considering only one forest class with average carbon stock, and 5–7 times higher when using literature default values or global emission maps. Carbon emissions from soil (up to 30 cm) were estimated for the main land change class. Due to the low emission factors from biomass, soils proved a key emission category, accounting for 30% of total land emissions that occurred during the monitoring period.

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Introduction

Managing the carbon footprint of the land use sector is currently a key focus for climate change mitigation in developing countries [1,2,101]. In terrestrial ecosystems, forests play a major role for the mitigation and adaptation to climate change via carbon storage, and furthermore by providing important ecosystem services such as water storage, soil fertility regulation and biodiversity preservation [3–5]. In recent years the United Nations collaborative initiative on Reducing Emissions from Deforestation and forest Degradation (REDD+) program has gained increasing attention in the policy arena, presenting a valuable incentive for developing countries to reduce emissions from forest land and at the same time promoting sustainable forest management and improving local livelihoods [6,102].

Assessing the amounts of carbon stored in forest ecosystems and their changes is key for quantifying their climate change mitigation capability and to design and implement REDD+ activities. Such tasks can be accomplished by combining ground and remote-sensing data at increasing levels of resolution and accuracy to move from estimates based on regional default values and global maps toward locally calibrated, accurate and comprehensive carbon emission and removal estimates [6–8,102]. Carbon changes due to deforestation in the 2000s have been estimated for the tropical regions [9, 11, 12,103] but most estimates consider only gross emissions from aboveground biomass, do not include forest regrowth processes and assume no biomass in the post-deforestation land uses. However, there is growing evidence that carbon removals due to forest regrowth play an important role in the carbon cycle at global and local scales [13–16], and their impact has been included in a recent assessment of carbon changes in the tropics during the 1990–2010 period [9]. Similarly, changes in soil organic carbon (OC), even though they tend to occur at a slower pace than those in the biomass pool, have a significant impact on net emissions occurring in the tropics [17,18]. Moreover, in order to move toward a complete carbon accounting, the residual carbon stock in deforested lands should be accounted for [19], and the carbon dynamics from all land change processes should be considered [8].

The land sector is one of the main emission sources in Vietnam, accounting for 53% of the total domestic greenhouse gases in 2000 [20]. Vietnam has been actively developing climate change mitigation and adaptation strategies during the last few years, and is currently in the process of identifying, planning and implementing land use practices that are sustainable,

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climate-smart and adapted to local needs [20]. Such strategies are driven by the imminent threat to be amongst the countries most severely affected by climate change impacts, with large areas at risk of increasing droughts and loss of agricultural crops [21,22,104].

Vietnam's forest coverage declined from 41 to 27% between 1943 and 1990, and during this period vast areas of primary forests were converted to secondary forests [105]. Threatened by the negative consequences of forest resources depletion [106], Vietnam has made considerable efforts to increase its forest cover during the last few decades, and expanded it to 39.7% of land area (13.5 million ha) in 2011 [23]. However, both forest gain and forest loss processes were identified in Vietnam during the 1990–2010 period [24]. In particular, the increase of forest area was mainly due to new plantations (2.9 million ha) and the expansion of natural forests on grasslands and shrublands, while deforestation and extensive degradation still remained prevalent with the result that over two thirds of Vietnam's natural forests are considered poor or regenerating [25,26].

To counteract these processes, the Vietnam National Strategy on Climate Change [27] and National Strategy on Green Growth [28] identified the protection, sustainable use and expansion of existing forests as key national priorities. Vietnam substantially improved its forest monitoring and forest inventory capacities between 2005 and 2015 [29] and adopted a nationwide and landscape-based approach for the REDD+ implementation. Among various strategies to mitigate the emissions from the land sector, forest protection has the highest carbon sequestration potential [30] and is a key measure to obtain the objective of reducing 20% of emissions from the land sector in the period 2011–2020 [107].

In order to support the implementation of the REDD+ program and other mitigation activities, it is necessary first to assess the carbon dynamics due to land cover change that occurred during a historical reference period. According to the Intergovernmental Panel on Climate Change (IPCC) Guidelines [31], greenhouse gas emissions and removals occurring on a certain piece of land can be calculated on the basis of two inputs: activity data and emission factors. Activity data consist in the areal extent of an activity that causes emissions or removals, usually referred to as area change data. Emission factors consist of the amount of emissions or removals per unit area related to a certain activity, usually referred to as changes in stocks between two land cover types. Such dynamics may then be used to estimate the Reference Emission Levels against which the REDD+ emission reductions can be accounted for.

In this context, the present study quantified the carbon emissions and removals in vegetation biomass owing to land cover changes that occurred between 2001 and 2010 in the Vu Gia Thu Bon River Basin in Central Vietnam. The contribution of carbon emissions from soil was also estimated for the main change processes. Activity data were obtained by mapping land cover and land cover changes using satellite images, while emission factors were derived from forest inventory data. The objectives of this study were to assess the main change processes and carbon pools driving net carbon emissions from the land sector, and the key factors (i.e. data and methods) that affect their estimation.

Data and methods

Study area

The study area consists of the Vu Gia Thu Bon (VGTB) River Basin, located in Central Vietnam and covering parts of the provinces of Quangnam, Danang and Kontum (Figure 1). The VGTB is one of the nine largest river basins and the fifth largest in volume in Vietnam [32]. The VGTB has been selected as the study area because it has been experiencing substantial and rapid changes in the last few decades. The economy is rapidly shifting from agriculture toward industry and services, and the economic growth rate of both Quangnam and Danang has increased around 10% each year, more than the average rate of Vietnam [33,34]. Droughts in the dry season and severe floods and typhoons during the wet season severely affect the region and are likely to be increased by climate change, especially in the coastal lowlands that are densely populated and characterized by intensive agriculture [22]. The mountain areas are less accessible and developed, but population growth, inland migration and the development of several hydropower projects during the last few years have caused substantial land changes and forest loss [35].

Land cover map for the year 2010

The land cover of the VGTB for the year 2010 was mapped at 30-m resolution using Landsat 7 satellite images, ancillary data sets and field observations to support the analysis of the land cover changes and the estimation of the carbon stocks. The map legend was based on the six IPCC classes, namely forest (areas with tree cover larger than 10%), grassland (areas dominated by grass, shrubs and woody regrowth), cropland, other land, settlement and wetland (water bodies and reservoirs).

The study area encompasses three Landsat tiles within which 12 Landsat scenes acquired during the dry season (January–April) with minimum cloud cover, haze contamination and phenological changes of vegetation (especially crop rotations) were selected. The dates and IDs of the Landsat images are reported in

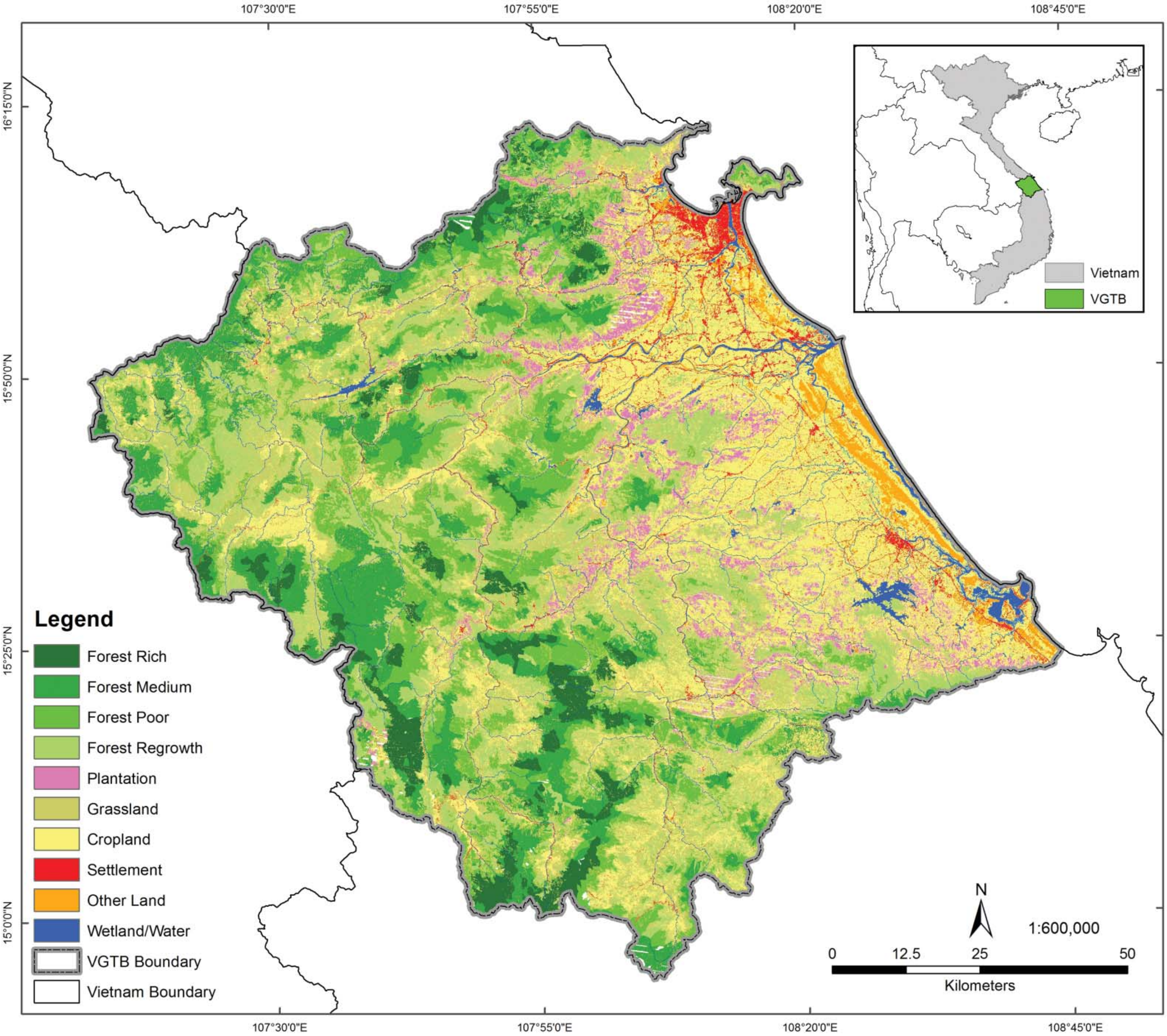

Figure 1. Land cover map of Vu Gia Thu Bon (VGTB) for the year 2010. Inset: Location of the VGTB River Basin, Central Vietnam.

Table S1. The images were pre-processed and harmonized using topographic correction [36] and radiometric normalization techniques [37]. Data gaps due to the Scan Line Corrector (SLC) failure were minimized [38] and clouds and cloud shadows were identified and removed [39] (Table S1). After pre-processing, the satellite data were classified into the six IPCC classes using the non-parametric Random Forest algorithm [40]. The algorithm was trained with field observations acquired during a dedicated field trip in March 2012 and further training data acquired through visual analysis of nine high-resolution satellite images (Spot 5, 2.5-m resolution). The effects of seasonal changes, which were especially marked for intra-annual crop rotations, were well represented in the training data set to obtain a consistent classification of the class “cropland.” Then, the 2010 forest map produced by the Forest Inventory and Planning Institute (FIPI) of Vietnam was used to distinguish five forest types within the areas classified as forest in our land cover map. The fusion of the two maps provided a land cover map with high spatial resolution (30 m) and thematic detail including 10 classes (forest rich, forest medium, forest poor, forest regrowth, forest plantation, grassland, cropland, settlement, other land, and wetland).

The map accuracy was computed only considering the six IPCC classes (i.e. without distinguishing the five forest types), because this information could not be reliably retrieved only from satellite data. The map was assessed for 300 validation points (stratified by class proportions) through visual interpretation of high-resolution Spot 5 satellite data acquired in 2010 and 2011, apart from limited areas where the images were taken in 2008.

Land cover change between 2001 and 2010

A land cover change map of the VGTB River Basin was created for the periods 2001–2005 and 2005–2010 using Landsat data. The base year was set to 2001 instead of 2000 because of the low data quality and large cloud coverage in the Landsat images during the year 2000. The change categories were defined as combinations of the six IPCC land cover classes. The changes within forest areas (i.e. within the five forest types identified in the FIPI map and including the changes from forest to plantation) were not considered because they could not reliably be mapped with automated classification of Landsat data.

The Landsat data were first pre-processed for cloud screening and gap-filling using the same procedures applied for the 2010 land cover map. The data gaps remaining after pre-processing covered 3 and 15% of the land area during the two monitoring periods (2001–2005 and 2005–2010, respectively) and were mostly located in the mountain areas on the western border of the study area. Due to the non-random nature of the land change processes (e.g. deforestation hotspots), it was preferred to avoid extrapolation of the detected changes in areas with no data, since the associated uncertainties could not be calculated and were likely to be large. The Landsat images were then transformed separately for each tile using the iteratively reweighted Multivariate Alteration Detection (iMAD) method [41], and the change pixels were identified by setting a threshold which was visually evaluated for each image pair using the iMAD change likelihood information layer. Due to the invariant properties of iMAD, radiometric normalization of the image pairs was not necessary. The type of change for the selected pixels was identified using the Random Forest classification algorithm [40], trained with reference data obtained through visual interpretation of the 2001, 2005 and 2010 Landsat mosaics and the 2010 land cover map. Seasonal changes due to agricultural practices that did not lead to a change in land cover were identified and removed by an additional change detection using the procedure indicated above of four Landsat images acquired in different seasons (days 82 and 290) of the year 2001.

Validation of the land cover change map was performed according to the good practices presented by Olofsson *et al*. [42] and Congalton [43]. In total, 340 validation samples were stratified by class area, with 290 points randomly sampled in the 25 change classes identified in the study area and 50 sample points in the six no-change classes. The reference data were extracted from Landsat images for the years 2000 and 2010 and from higher resolution data (Spot5, Rapideye, GoogleEarth) when available. Each reference point and its direct neighborhood were interpreted by visual analysis to identify the most common change class present within the nine pixels.

Carbon emissions and removals between 2001 and 2010

The amounts and spatial distribution of the carbon emissions and removals in the VGTB were obtained by combining the land cover change map for the period 2001–2010, which provided the activity data, with the emission factors, mostly derived from ground observations. The emission factors were obtained using the stock-change approach by subtracting the mean carbon stock of the class after the change to that of the class before the change [44]. Positive emission factors indicate release of carbon from land to the atmosphere (emissions) while negative emission factors indicate absorption of carbon from the atmosphere to the land (removals).

The carbon pools included in this study were above- and belowground biomass of living vegetation, which are responsible for the vast majority of carbon emissions and removals in most terrestrial ecosystems. In addition, carbon emissions from soils were estimated for the main land cover change category. Carbon dynamics that did not result in land cover change but occurred within a stable land cover class (as forest degradation or forest growth) were not considered. The carbon emissions and removals were converted to CO_2 equivalent units (CO_2) using the conversion factor of 44/12.

In the case of forest loss, carbon dynamics depend on the type of forest affected by the change activity. This information was not available from the 2001–2010 land cover change map (which identifies only one forest class) and was obtained from the 2010 land cover map using the proximity criterion, attributing each patch of forest converted to another land cover class to the spatially nearest type of forest. Changes from non-forest to forest always assumed that the conversion was to regrowth forest, since other forest classes can develop only in timeframes longer than 10 years (the monitoring period of this study).

The carbon emissions obtained from this study were compared with the emission databases for tropical deforestation of Zarin *et al*. [12] and Harris *et al*. [10]. Zarin *et al*. [12] estimated emissions from aboveground biomass for the period 2001–2013 by combining the Hansen *et al*. [45] global forest cover change map with the Baccini *et al*. [46] pantropical biomass map. By contrast, Harris *et al*. [10] estimated emissions from above- and belowground biomass for the period 2000–2005 by combining the Hansen *et al*. [47] global forest loss map with the Saatchi *et al*. [48] pantropical biomass map. The emission estimates for the study area (VGTB) were harmonized with regard to time period, carbon pool and assumptions (i.e. no biomass remaining after deforestation) before comparison (see Discussion).

Carbon stocks and emission factors of biomass

In this study biomass is defined as the total amount of above- and belowground organic matter in living vegetation expressed in units of dry weight. The carbon stock density of aboveground biomass (AGB) was estimated on the basis of forest inventory plots while, due to the absence of direct measurements, the belowground compartment (BGB) was derived from AGB using the average IPCC root-to-shoot ratios (R) in the tropical moist ecoregion: 0.205 for AGB $<$ 125 Mg/ha and 0.235 for AGB $>$ 125 Mg/ha [49]. The biomass values were converted to carbon units using the conversion factor of 0.5 [44]. Hence, carbon stock in biomass (C) was obtained as

$$C = (AGB + BGB) \cdot 0.5 = (\mathrm{AGB} + (\mathrm{AGB} \cdot \mathrm{R})) \cdot 0.5 \quad (1)$$

The field data used in this study included two different data sets. The first data set consists of 2994 plots of 0.05-ha size collected by the FIPI during the National Forest Inventory in the Quang Nam province between 2007 and 2009 according to a systematic sampling strategy. The second data set consists of 89 plots of 0.126-ha size acquired in 2011 and 2012 by a dedicated field campaign with a random stratified sampling approach at locations expected to be deforested (i.e. nearby deforestation hotspots), representative of the carbon emission from forest loss. The data collected in the field consist of the diameter at breast height (DBH) and species identification for all trees with DBH $>$ 5 cm. The wood density of the tree species was identified using the Global Wood Density Database [50,108]. For the species not included in the wood density database, the mean value of the species belonging to the same genus and located in the South-East Asia region was used, while the average wood density value of all species recorded in the plots was applied for the species that could not be identified in the field. The AGB was estimated using the generalized allometric equation for moist tropical forest based on DBH and wood density provided by Chave *et al.* [51]. The field data were then stratified by the 2010 land cover map to estimate the total and average carbon stock per class and related standard error, and to convert the 2010 land cover map to a carbon stock map.

Since no plots were located in the classes cropland, settlement, other land and wetland, the IPCC Tier 1 default biomass density values [31] were applied. The carbon density was considered equal to 5 Mg C/ha in croplands (table 5.9 in [31]). In the case of settlement, other land and wetland, no reference data for their carbon stocks were available but the IPCC Tier 1 default values assume no carbon remaining in biomass after conversion to these land categories. Given the small areal extent, in this study their carbon stock was also assumed to be zero for the opposite changes (i.e. from these classes to other land cover classes). Having the same emission factors, the classes settlement, other land and wetland were grouped in the class "no vegetation" for emission calculations.

Carbon stocks and emission factors of soils under forest change

Field data or literature values representative of the emissions factors for soil and litter in the VGTB were not available prior to this study [17]. Since it was not feasible to acquire field data for all land change categories due to time and cost constrains, carbon stock changes were estimated only for the main change process observed in the VGTB (i.e. the conversion of forest to cropland) through a dedicated sampling campaign performed in 2012. Field sample plots were also acquired to assess whether relevant emissions were caused from the conversion of forest to plantation (a change process that was not included in the land cover change map) and to quantify the emissions occurring after deforestation but before a follow-up land use is implemented (forest to bare soil).

The field plots were located using a stratified random sampling design using land cover, land cover change and soil type as the stratifying variables. The field observations focused on three sites that presented large deforestation areas (the districts of Tra Giac, Tra Leng and Tu Ba) and on land cover classes occurring on Acrisol, which is the dominant soil group occurring on 74.7% of the study area [52]. In total, 27 plots were sampled in deforested areas and in forests representative of the soil organic carbon (SOC) stocks before deforestation, identified as forests located in proximity and with similar environmental conditions to deforested areas. At each sampling plot, five individual soil cores were taken from the first 30 cm within a 20 m × 20 m area. After removal of coarse roots and stones with a diameter of $>$ 2 mm, mineral soil samples were dried at 40°C and litter samples at 70°C. Total carbon (TC) concentrations were determined by dry combustion. After removal of organic carbon (OC) by ignition at 450°C for 16 h, inorganic C was quantified with the same elemental analyzer. OC concentrations of the mineral soil were calculated as the difference between TC and inorganic C. Bulk density of the mineral soil was calculated with the mass of the oven dry soil (105°C) and the core volume. OC stocks were calculated based on bulk density, relative contribution of fine earth material (soil $<$ 2 mm) to total soil mass, layer thickness and OC concentration.

Uncertainty assessment

Uncertainty about the carbon emissions was assessed by computing and propagating the uncertainty about the activity data and the uncertainty concerning the emission factors. The uncertainty metric used in this study is one standard deviation (σ) of the estimated values, which are the total change area for the activity data and the mean carbon stock change density for the emission factor. These two components were considered uncorrelated because they were obtained with independent data, namely satellite images and forest inventory plots. On this basis, the uncertainty of the emission estimates was computed using analytical error propagation equations for addition and multiplication of two independent random variables.

Uncertainty about the activity data (i.e. the area of each land change category) was computed on the basis of the validation results of the land cover change map. With p_{ij} denoting the probability of correctly identifying a change from class i to class j, and assuming that classification errors are spatially uncorrelated, the uncertainty of the respective class area ($\sigma_{ij}(AD)$) was computed as

$$\sigma_{ij}\ (AD) = \sqrt{N_{pixel(ij)} \cdot Area^2_{pixel} \cdot p_{ij} \cdot (1 - p_{ij}\ )} \qquad (2)$$

where $N_{pixel(ij)}$ represents the number of pixels of the change class ij and $Area_{pixel}$ the pixel area, equal to 0.09 ha for all classes.

Uncertainty about the emission factors was computed by summing the uncertainties concerning the carbon stock density of the land cover classes before and after the change. Since carbon stocks were obtained as the sum of the above- and belowground components (Equation 1), the uncertainties were computed separately for the above- and belowground biomass and then summed as indicated below. The uncertainty about the carbon stock change between the class i and j (emission factor) for aboveground biomass ($\sigma_{ij}\ (AGB)$) was computed as

$$\sigma_{ij}\ (AGB) = \sqrt{\sigma_i(AGB)^2 + \sigma_j(AGB)^2} \qquad (3)$$

where $\sigma_i(AGB)$ and $\sigma_j(AGB)$ represent the standard error of the mean aboveground carbon stock of land cover class i and j, computed on the basis of the field data as the ratio between the standard deviation of the plot biomass and the square root of the number of plots.

Since the belowground biomass for the class i was computed by multiplication of the mean aboveground biomass (AGB_i) with a root-to-shoot ratio (R_i) (Equation 1), the respective uncertainty ($\sigma_i(BGB)$) included the uncertainty about the input variables as follows:

$$\sigma_{ij}\ (E) = \sqrt{[AD_{ij}{}^2 \cdot \sigma_{ij}(\mathrm{EF})^2] + [\mathrm{EF}_{ij}{}^2 \cdot \sigma_{ij}(\mathrm{AD})^2] + [\sigma_{ij}(\mathrm{AD})^2 \cdot \sigma_{ij}(\mathrm{EF})^2]} \qquad (4)$$

Lastly, the uncertainty about the total emissions for all land changes was obtained by summing the uncertainty concerning the emissions for each change category as in Equation (3).

Results

Land cover map for 2010

The VGTB River Basin comprises 12,385 km^2 and in the year 2010 almost half of the land area was covered by forest (47%), followed by cropland (26%) and grassland (20%), while smaller areas were occupied by settlement (3%), wetland (i.e. water bodies; 3%) and other land (2%) (Figure 1; Table S1). Among forest areas, regrowth forest was the most common forest type (33%), followed by poor forest (25%) and medium forest (25%), while rich forest represented only 10% of the forest areas and plantations (mostly short-term rotations of *Acacia*) were established on 8% of forest land. The overall accuracy of the land cover map was equal to 82% (Table S1). The users' and producers' accuracy of the six IPCC classes were always higher than 80% with the exception of cropland and settlement (71 and 68% users' accuracy, respectively), and grassland (68% producers' accuracy).

Land cover change in 2001–2010

The change detection indicated that 4.7% of land area was affected by change during the period 2001–2010, equal to 5770 ha/year (Table S2). The change rate was equal to 3.1% during the sub-period 2005–2010 and 1.6% during the sub-period 2001–2005. The gross deforestation rate proved to be about 2.2% of land area over the 2001–2010 period, indicating an average annual deforestation rate of 0.22% that was equally spread over the two sub-periods. The gross deforestation was partly counterbalanced by forest regrowth (0.58% of land area), which mostly occurred during 2005–2010 (0.48%) and only 0.10% during 2001–2005.

The most prominent change category during the 2001–2010 period was the transition from forest to cropland, which occurred on 1.43% of land area, while the reverse process (from cropland to forest) was detected on 0.43% of land area (Figure 2). Another prominent change was the transition of grassland to cropland, which occurred on 0.84% of land area, and the urbanization process with expansion of new settlements on 0.38% of land area, while almost no decrease of settlement was mapped. The validation of the land cover change map, computed after aggregating the

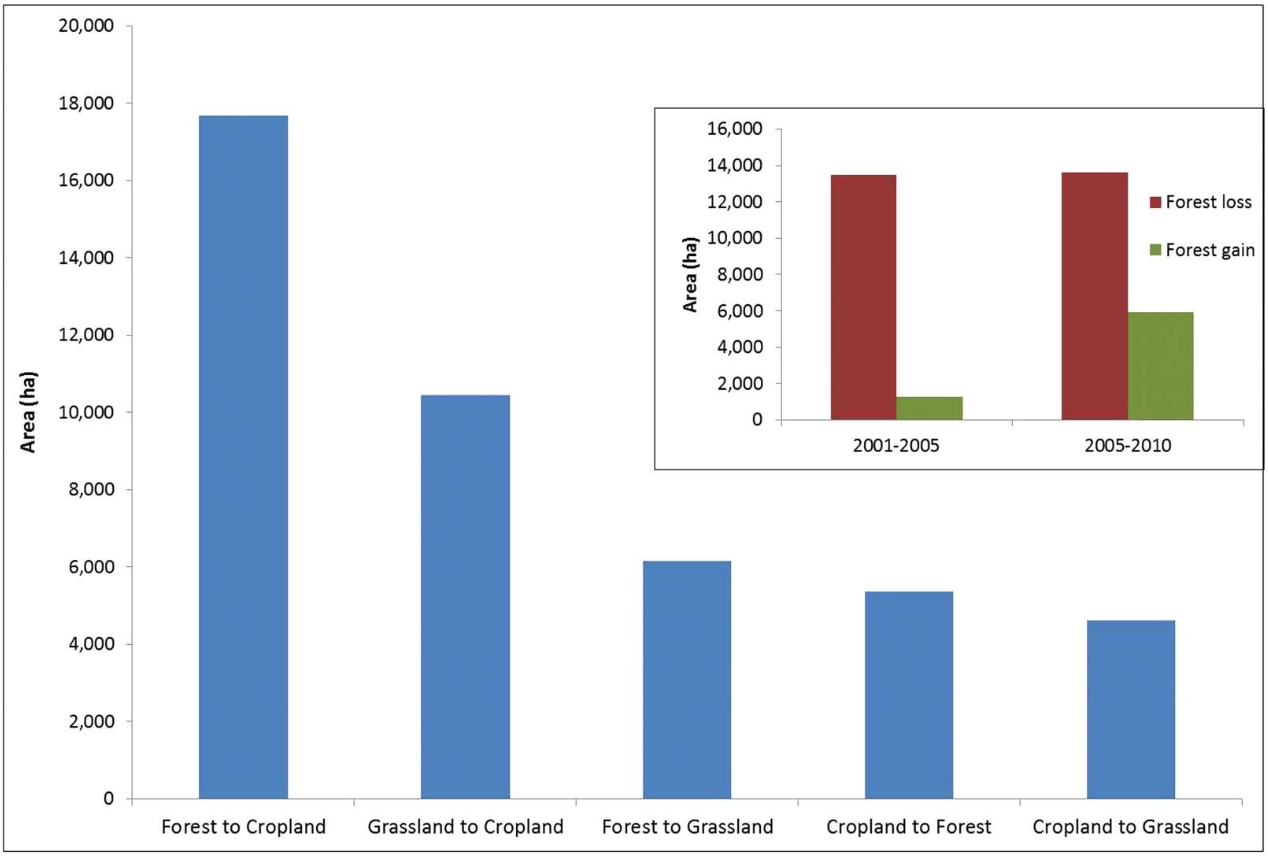

Figure 2. Area change for the main land cover change categories in the Vu Gia Thu Bon (VGTB) River Basin for 2001–2010. Inset: Summary of change area for forest loss (from forest to a non-forest class, in red) and forest gain (from a non-forest class to forest, in green) for the two monitoring periods (2001–2005 and 2005–2010).

classes settlement, other land and wetland into the class "no vegetation," indicated that the overall accuracy was 81% and the producers' and users' accuracies were higher than 70% (Table S3).

Carbon stocks and emission factors of biomass

The vegetation of VGTB stores 42.7 Tg carbon in its biomass, with 34.9 Tg in aboveground biomass and 7.9 Tg in belowground biomass. The distribution of carbon stocks varies considerably among the land cover classes (Figure 3). Forests store about 92% of the carbon stock of VGTB on about 47% of the land area, with most carbon (80%) contained in rich, medium and poor forest (i.e. excluding regrowth and plantation) on 28% of the land area. Rich forests alone store 28% of total carbon on 5% of the land area while plantations present a similar extent (4%) but contain only 2% of the carbon stock. Medium forest covers the same extent as poor forest (12% of land area for each class) but stores double the amount of carbon (35 vs. 18% of total stock, respectively), while regrowth areas contain 10% of carbon on 15% of the land area. Almost half of the VGTB (46% of the land area) is covered by low-carbon cropland and grassland, which store only 9% of total carbon, while the remaining 7% of land (settlement, other land and wetland) was considered to have no carbon stock in vegetation biomass.

The carbon stock density varies considerably among the vegetation strata, and the differentiation of forests into rich (206 Mg C/ha), medium (102 Mg C/ha), poor (44 Mg C/ha), regrowth (22 Mg C/ha) and plantation (16 Mg C/ha) forest represents appropriately the differences in carbon density (Table 1). Grassland and cropland showed substantially lower mean values (8 and 5 Mg C/ha, respectively). As a consequence, the emission factors in the conversion of a forest to a non-forest class varied largely depending on the forest type involved in the change process, ranging from 8 to 206 Mg C/ha (Table 2). The emission factors for the conversion of non-forest to forest presented a smaller range, varying from −14 to −22 Mg C/ha (where negative emission factors indicate carbon removals from the atmosphere), due to the fact that only the transition to regrowth forest was possible within the monitoring period of 10 years. Change process among non-forest classes presented the lowest emission factors, ranging from 8 to -8 Mg C/ha. Regarding uncertainty, the emission factors for aboveground biomass from forest-related changes (derived from the field data) presented lower uncertainty (about 2–10% of the emission factor) than the corresponding values for belowground biomass (derived from [49]), which were about 5–20% of the emission factor (Table 1).

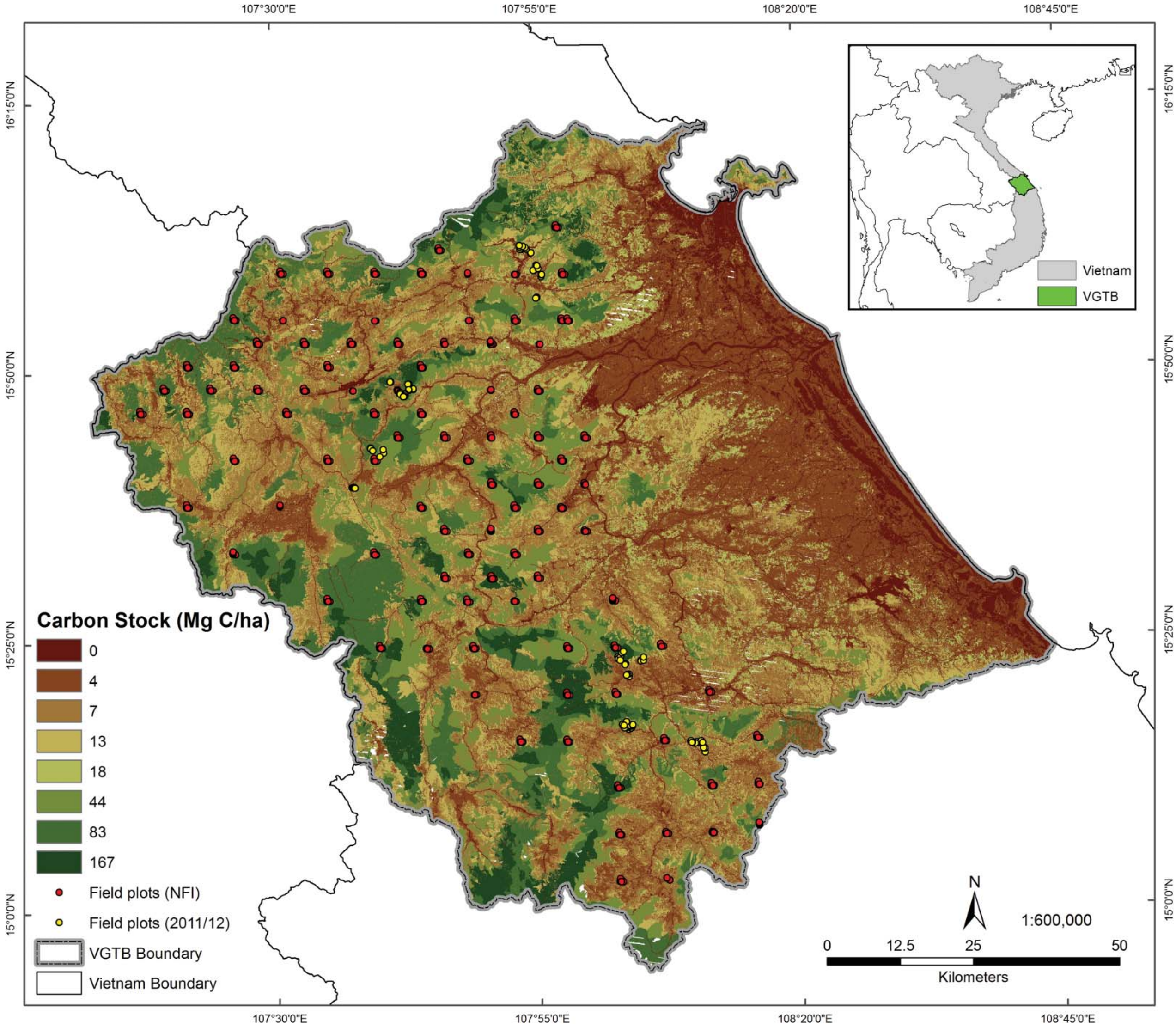

Figure 3. **Map of the carbon stock density in aboveground biomass for the year 2010 in the Vu Gia Thu Bon (VGTB) River Basin, and location of the forest inventory plots acquired by the National Forest Inventory (NFI) and by an ad-hoc field campaign in 2011 and 2012. Inset: location of the VGTB River Basin, Central Vietnam.**

Carbon stocks and emission factors of soils under forest change

The mean SOC density in forest areas (including plantations) was 48.7 ± 3.8 Mg C/ha (Table 3). When considering forest and plantations separately, the mean SOC stock for plantation (49.6 ± 5.4 Mg C/ha) was not significantly different from the SOC stocks of forest excluding plantations (48.1 ± 4.9 Mg C/ha), indicating that the emissions for the related change process (conversion of forest to plantation) were negligible. The SOC stocks in recently deforested areas were lower than those in forests, being equal to 43.2 ± 4.8 Mg C/ha after deforestation (forest converted to bare soil) and 40.8 ± 5.5 Mg C/ha in forest converted to croplands during the period 2001–2010. The OC stocks in the litter layer showed similar patterns with the highest (and very similar) values in forest (1.10 ± 0.14 Mg C/ha) and plantation (1.09 ± 0.06 Mg C/ha) areas, and lower values in croplands (0.65 ± 0.09 Mg C/ha), while no OC stocks could be calculated in recently deforested areas

Table 1. **Mean carbon stock density values (± standard error) for aboveground (AGB), belowground (BGB) and total (AGB+BGB) biomass per land-cover class.**

		Carbon stock (Mg C/ha)			
Land cover class	No. plots	AGB	BGB	AGB+BGB	Source
Forest rich	970	166.8 ± 2.5	39.2 ± 1.9	206.0 ± 3.2	Field data
Forest medium	629	83.0 ± 1.5	19.5 ± 3.0	102.5 ± 1.8	Field data
Forest poor	581	44.5 ± 1.3	9.1 ± 1.6	53.6 ± 2.1	Field data
Regrowth	352	18.2 ± 0.7	3.7 ± 0.7	22.0 ± 1.0	Field data
Plantation	79	12.9 ± 1.3	2.6 ± 0.5	15.5 ± 1.4	Field data
Grassland	472	6.5 ± 0.4	1.3 ± 0.2	7.9 ± 0.4	Field data
Cropland	0	4.0 ± 1.5	1.0 ± 0.3	5.0 ± 1.5	IPCC Tier 1

Table 2. **Area, emission factors (EF) for aboveground (AGB), belowground (BGB) and total biomass (AGB+BGB), and total carbon emissions (emissions) (± standard error) per land-cover change class in the Vu Gia Thu Bon (VGTB) River Basin during the period 2001–2010. The class "no vegetation" includes the classes settlement, other land and wetland, which have the same EF.**

		EF (Mg C/ha)			
Change category	Area (ha)	AGB	BGB	AGB+BGB	Emissions (Gg CO_2)
Forest rich to cropland	28 ± 1	163 ± 3	38 ± 2	201 ± 4	20 ± 1
Forest medium to cropland	488 ± 2	79 ± 2	18 ± 1	97 ± 2	1745 ± 4
Forest poor to cropland	482 ± 2	41 ± 2	8 ± 2	49 ± 3	86 ± 5
Regrowth to cropland	10,630 ± 10	14 ± 2	3 ± 1	17 ± 2	661 ± 70
Plantation to cropland	6046 ± 7	9 ± 2	2 ± 1	11 ± 2	233 ± 45
Forest rich to grassland	38 ± 0	160 ± 3	38 ± 2	198 ± 3	28 ± 0
Forest medium to grassland	256 ± 1	76 ± 2	18 ± 1	95 ± 2	89 ± 2
Forest poor to grassland	1328 ± 2	38 ± 1	8 ± 2	46 ± 2	223 ± 10
Regrowth to grassland	3583 ± 3	12 ± 1	2 ± 1	14 ± 1	185 ± 14
Plantation to grassland	947 ± 2	6 ± 1	1 ± 1	8 ± 1	27 ± 5
Forest rich to no vegetation	15 ± 1	167 ± 3	39 ± 2	206 ± 3	12 ± 0
Forest medium to no vegetation	165 ± 2	83 ± 2	19 ± 1	102 ± 2	62 ± 1
Forest poor to no vegetation	267 ± 2	44 ± 1	9 ± 2	54 ± 2	52 ± 2
Regrowth to no vegetation	2040 ± 6	18 ± 1	4 ± 1	22 ± 1	164 ± 7
Plantation to no vegetation	797 ± 4	13 ± 1	3 ± 1	16 ± 1	45 ± 4
Cropland to forest	5358 ± 0	−14 ± 2	−3 ± 1	−17 ± 2	−333 ± 35
Cropland to grassland	4619 ± 8	−3 ± 2	0 ± 0	−3 ± 2	−49 ± 27
Cropland to no vegetation	1346 ± 0	4 ± 1	1 ± 0	5 ± 2	25 ± 8
Grassland to forest	987 ± 0	−12 ± 1	−2 ± 1	−14 ± 1	−51 ± 4
Grassland to cropland	10,451 ± 7	3 ± 2	0 ± 0	3 ± 2	111 ± 61
Grassland to no vegetation	3294 ± 6	7 ± 0	1 ± 0	8 ± 2	95 ± 18
No vegetation to forest	848 ± 0	−18 ± 1	−4 ± 1	−22 ± 1	−68 ± 3
No vegetation to cropland	1221 ± 0	−4 ± 1	−1 ± 0	−5 ± 2	−22 ± 7
No vegetation to grassland	257 ± 0	−7 ± 0	−1 ± 0	−8 ± 0	−7 ± 0
No vegetation to No vegetation	2247 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Total	57,740 ± 20				1761 ± 117

due to the absence of a litter layer as a consequence of the burning practices.

The conversion of forest to cropland resulted in an SOC loss for the 10-year monitoring period in the mineral soil of 7.9 ± 4.0 Mg C/ha, while the emissions immediately after deforestation were lower (5.4 ± 3.6 Mg C/ha). The emissions from the litter layer were only 0.5 ± 0.1 Mg C/ha in the conversion of forest to cropland and 1.10 ± 0.08 Mg C/ha immediately after deforestation (assuming that the litter layer is burned). Hence, in most cases the emission factors relative to the monitoring period for soils were smaller than those for aboveground biomass and presented larger relative uncertainties due to the smaller sample size.

Table 3. **Mean OC stock values (± standard error) for mineral soil and litter samples per land cover class. The values for forest and plantation are first presented separately and then combined in the class "forest and plantation," the values for cropland refer to OC stocks in agriculture areas established between 2001 and 2010 on forest soil, and the values for no vegetation refer to OC stocks in bare soil due to recent deforestation.**

		OC stock (Mg C/ha)	
Land cover class	No. plots	Mineral soil	Litter
Forest	9	48.1 ± 3.0	1.1 ± 0.1
Plantation	6	49.6 ± 3.3	1.1 ± 0.1
Forest and plantation	15	48.7 ± 2.1	1.1 ± 0.1
Cropland (from 2001)	6	40.8 ± 3.3	0.6 ± 0.1
No vegetation	6	43.2 ± 2.9	0 ± 0

Carbon emissions and removals in 2001–2010

Changes in the land cover that occurred in the VGTB between 2001 and 2010 caused net emissions of about 1.76 ± 0.12 Tg CO_2 equivalent (Figure 4; Table 2). The vast majority of carbon emissions were due to forest loss, with the conversion of forest to cropland being the single most important source of CO_2, accounting for 67% of net emissions (1.17 ± 0.08 Tg CO_2), followed by the conversion of forest to grassland that caused 31% of net emissions (0.55 ± 0.02 Tg CO_2). When considering the forest type, most of the emissions from agriculture-driven deforestation occurred on regrowth forest (0.66 ± 0.07 Tg CO_2), characterized by a low emission factor (17 ± 2 Mg C/ha). The net emissions were mainly due to the loss of carbon from aboveground biomass (83.2%), while emissions from belowground biomass contributed to 16.8% of the net carbon release, reflecting the root-to-shoot ratios used to compute the belowground biomass.

Substantial removals were due to the change of non-forest areas to forest (regrowth), which absorbed 0.45 ± 0.04 Tg CO_2, equal to 22% of gross emissions from deforestation and 26% of net land emissions (Table 2). Most removals (74%) were due to the conversion of cropland to forest. Carbon changes due to conversion among non-forest classes produced small carbon emissions or removals, with a net effect of carbon release equal to 9% of net emissions, mostly due to the conversion of grassland to

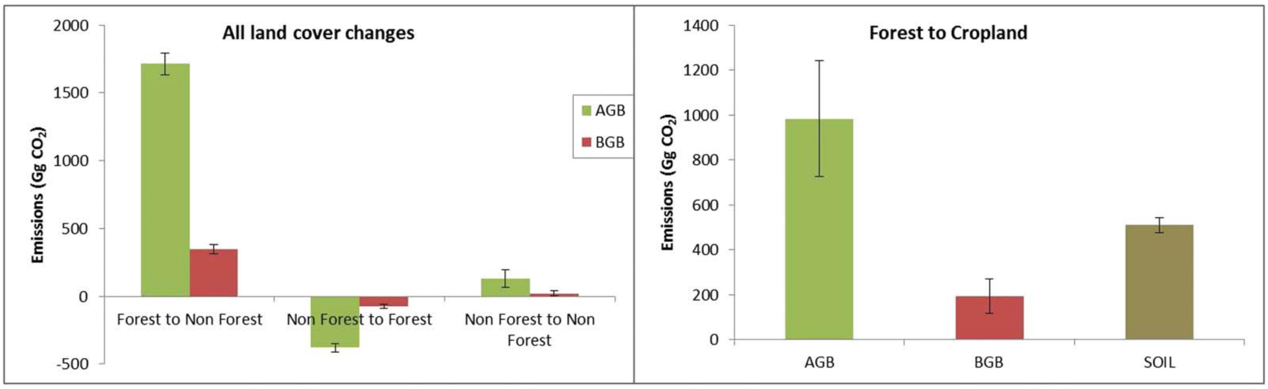

Figure 4. Carbon emissions and removals from aboveground (AGB) and belowground (BGB) biomass for aggregated change classes in the Vu Gia Thu Bon (VGTB) River Basin during the period 2001–2010 (left), and carbon emissions from AGB, BGB and soil for the change in class from forest to cropland (right). The non-forest class includes grassland, cropland, settlement, other land and wetland. The uncertainty bars represent ± 1 standard error.

cropland. The spatial distribution of the emissions and removals shows that the majority of the carbon changes occurred in the most accessible areas, namely the lowlands in the coastal areas and along the river valleys in the midlands and uplands (Figure 5).

Emissions from soil were estimated for the conversion of forest to cropland (the main change class in terms of area and emissions), and were equal to 43% of emissions from biomass (0.51 ± 0.26 Tg CO_2). Hence, when considering the three carbon pools (aboveground biomass, belowground biomass and soil carbon), soil carbon accounted for 30% of total emissions from this change class (Figure 4).

Discussion and conclusions

Net carbon emissions from land cover change in the VGTB during the last decade were about 1.1% of the existing stocks and were mostly caused by the conversion of forest to cropland. Most of the emissions were related to the loss of aboveground biomass from forests, showing that the estimation of this carbon pool has the largest impact on the net land emissions. Our study indicates that the stratification by forest type is a critical factor in the estimations because the VGTB is characterized by large variability of forest conditions, and deforestation did not occur on “average” forests but mostly affected the regrowing forests (60%) and the plantations (29%) characterized by carbon stock densities (16–22 Mg C/ha) substantially lower than those of medium or rich forest (103–206 Mg C/ha). Regrowth forest and plantations are located in accessible areas, and were largely affected by the expansion of agriculture and the slash-and-burn practices. In contrast, the high-carbon forests remain unaffected only in the remote mountain areas where difficult accessibility and ground steepness prevented their conversion to other land uses.

It is remarkable that, if only one forest class with average carbon stock was considered without further stratification by forest type, the net emissions of VGTB from the above- and belowground biomass would increase about 4 times (Table 4). In fact, the mean aboveground forest carbon stock in VGTB calculated as simple average of the field plots would be 81 Mg C/ha and the corresponding mean emission factor for forest (calculated as ratio between the total aboveground emissions from deforestation and the respective area) would be 77 Mg C/ha, while it was 21 Mg C/ha when considering the five forest types. Furthermore, if the average forest carbon stock were calculated on the basis of a literature value for tropical forest instead of from local field data, the net emissions would have been larger. For example, using the reference emission factor for aboveground biomass in the Brazilian amazon applied by the Amazon Fund (100 Mg C/ha) [53] would increase the net emission estimates from above- and belowground biomass in the VGTB by almost 5 times, while using the mean IPCC Tier 1 default value (140 Mg C/ha in the tropical rain forest ecozone in continental Asia) [31] would increase the net emissions by about 7 times.

Larger emissions in the VGTB were also estimated from two existing tropical deforestation emission databases (Table 4). According to the recent emission estimates by Zarin *et al*. [12], the gross emissions from deforestation from aboveground biomass for 2001–2010 in the VGTB were about 6.4 times higher than our estimates (recomputed considering the same assumptions, i.e. no biomass in the follow-up land cover classes). The difference between the two data sets was mostly due to the forest carbon stock values. According to the biomass map used by Zarin *et al*. [12], the mean forest carbon stock in the deforested areas in the VGTB was about 93 Mg C/ha, 4.4 times higher than the value derived from the field data (21 Mg C/ha) in our study (computed as the ratio between total emissions from deforestation and the corresponding area, considering no biomass in the follow-up land cover). Instead, the deforestation area estimates were more

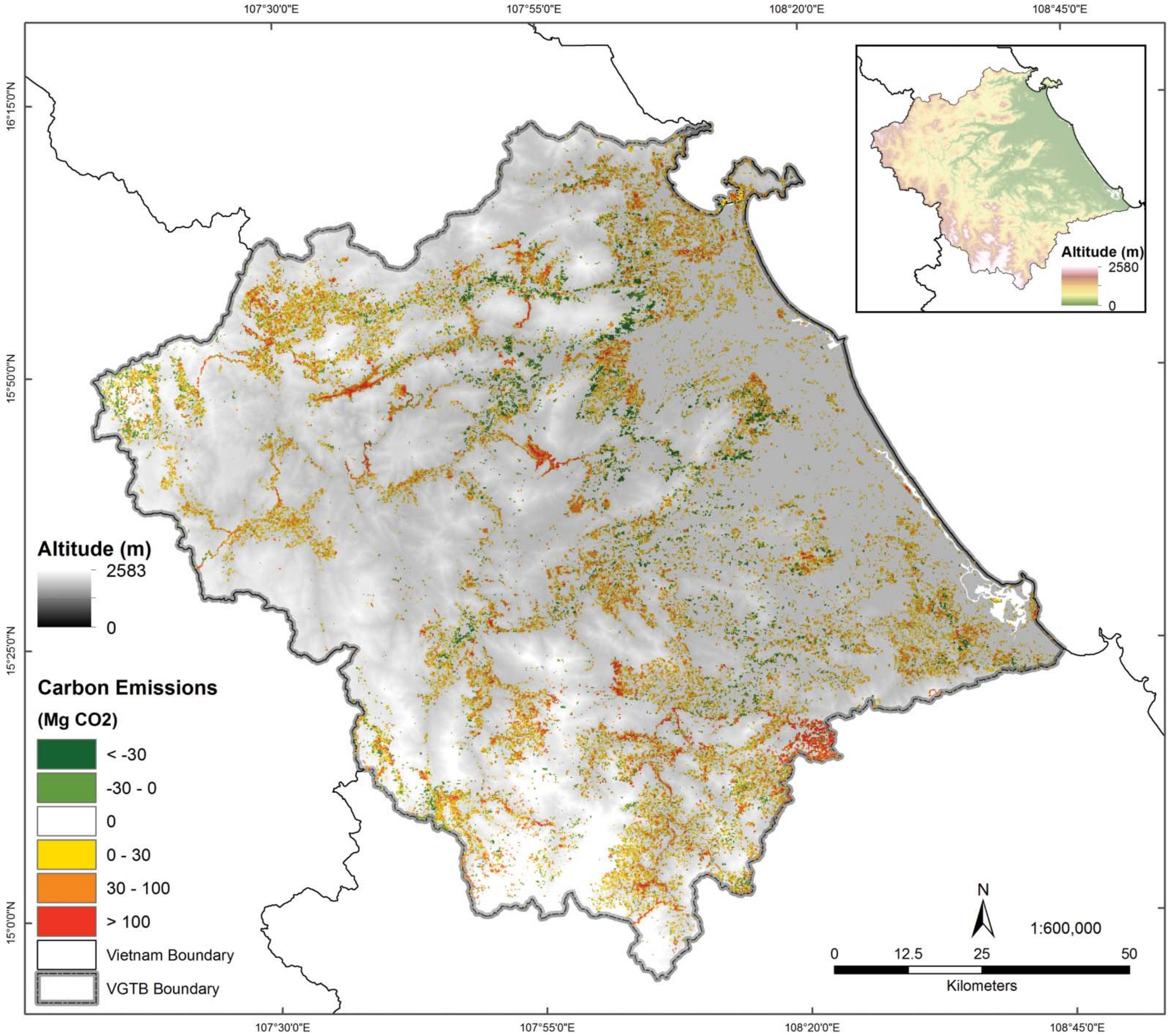

Figure 5. **Carbon emissions from above- and belowground biomass in the Vu Gia Thu Bon (VGTB) River Basin due to land cover changes between 2001 and 2010, superimposed on the elevation map. Negative emissions represent removals. The emissions are aggregated at 200 m and the elevation map is shown at 20% trasparency for display purposes. Inset: Elevation map of the VGTB River Basin derived from Shuttle Radar Topography Mission data.**

similar and accounted for a smaller part of the difference in the emissions. The forest loss area in VGTB during 2001–2010 according to Hansen *et al.* [45] (the forest change map used by Zarin *et al.* [12]) was 1.5 times higher than our estimates, and showed a similar spatial pattern.

Similarly, higher emissions from deforestation were estimated from the tropical database of Harris *et al.* [10] (Table 4). This data set estimated yearly gross emission from deforestation from above- and belowground biomass for the VGTB to be 5.3 times higher when compared to the corresponding value of our study, recomputed considering the same assumption of no biomass in the follow-up land cover classes (1.37 and 0.26 Tg CO_2/year, respectively). It is important to note that the substantial differences observed at

Table 4. **Comparison of emission estimates obtained from different data sources for Vu Gia Thu Bon (VGTB) during 2001–2010. The emission estimates from this study are harmonized to the same category before comparison: net emissions from all land changes ("net land") or gross emissions from forest loss with no biomass in the follow-up land-cover classes ("gross forest"). The emission factors (EF) are mean values computed as the ratio between total emissions and the corresponding area change.**

Ref.	Emission category	Carbon pool	EF (Mg C/ha)	Emissions (Gg CO_2)	Difference (%)
This study	Net land	AGB+BGB	20.7	1761	-
Average VGTB plots	Net land	AGB+BGB	81.2	6937	394%
BNDES, 2009[53]	Net land	AGB+BGB	100.0	8591	488%
IPCC [31]	Net land	AGB+BGB	140.0	12,418	705%
This study	Gross forest	AGB+BGB	20.7	2563	-
Harris *et al.* [10]	Gross forest	AGB+BGB	-	13,678	534%
This study	Gross forest	AGB	21.3	2119	-
[Zarin *et al.* 12]	Gross forest	AGB	93.5	13,557	640%

local scale between our estimates and the two tropical emission databases do not provide any indication of their accuracy, which should be computed using a statistical sampling design representative of the complete study area (i.e. the tropical belt). Rather, such differences indicate the relevance of using local field data in contexts characterized by particular forest dynamics, as is the case in the VGTB where most deforestation occurred in low-carbon forest areas.

As a consequence of the low emission factors from biomass, the removals from forest regrowth and the emissions from soil were relevant, accounting for 26 and 30% of net emissions, respectively (with the former value referring to all land changes and the latter only to the conversion of forest to cropland). While this result strongly supports the importance of regrowing forests and soil in land carbon accounting, their contribution to the total emissions is expected to be lower when deforestation events occur on forests with average or higher C stocks. On the other hand, since the carbon removals from forest regrowth and emissions from soil are slow processes that continue to occur well beyond the time frame of this study (10 years), their role in carbon accounting becomes more relevant with longer monitoring periods and when considering legacy effects.

Similarly, this study found that the SOC stocks of forest and plantation were not significantly different, indicating that emissions for this change process were negligible within the 10-year period. However, considering that most plantations were recently established on forest soils, the related soil emissions may increase in longer time frames. This may not be the case for the conversion of young or degraded forest to plantations, as SOC stocks of forest regrowth and *Acacia* plantations were found not significantly different from each other in North and South Vietnam under the dominant soil group Acrisol [54]. However, if the total ecological value of forests beyond SOC sequestration and timber production is considered, natural forests and regrowths can provide or restore important ecosystem services and biodiversity compared to plantations.

Lastly, C changes within stable land cover classes were not considered in this study due to the absence of reliable data but their impact on the total land carbon balance may not be negligible and should be further investigated, especially in areas where substantial transitions between different forest types occur.

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