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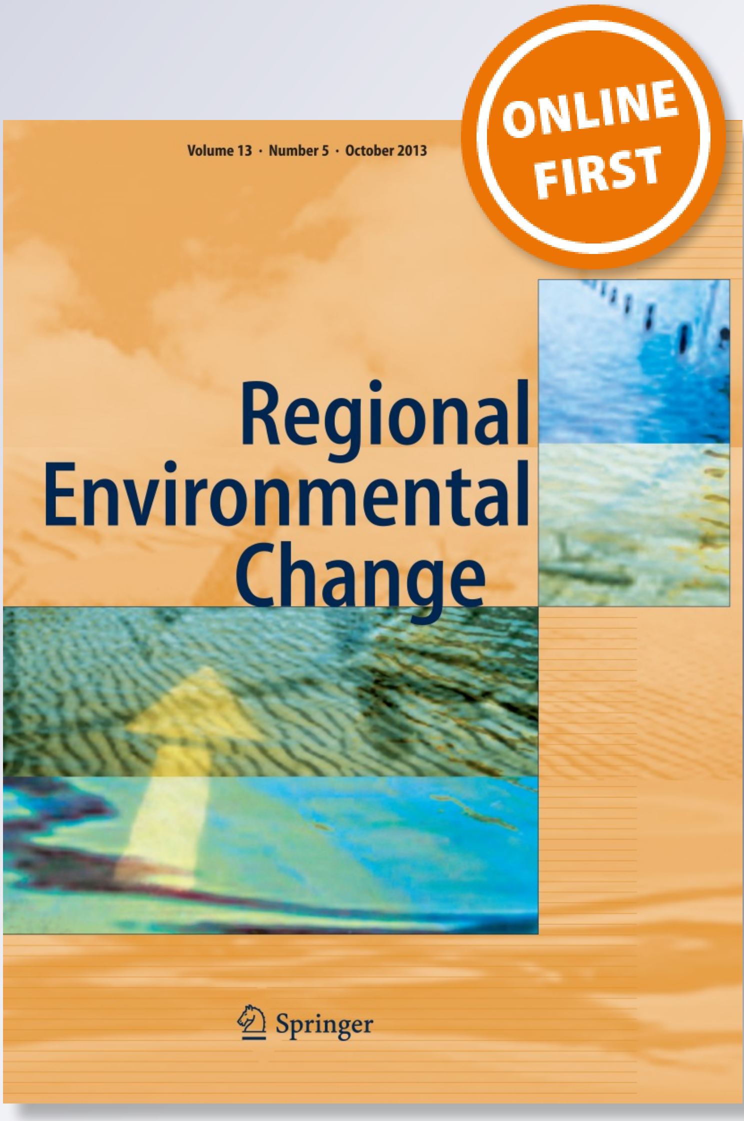

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ORIGINAL ARTICLE

Agroforest's growing role in reducing carbon losses from Jambi (Sumatra), Indonesia

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Abstract This paper examines the size and intensity of changes among five land categories during the two time intervals in a region of Indonesia that is pioneering negotiations concerning reducing emissions from deforestation and forest degradation (REDD). Maps at 1973, 1993, and 2005 indicate that land-cover change is accelerating, while carbon loss is decelerating in Jambi Province, Sumatra. Land dynamics have shifted from Forest loss during 1973–1993 to Agroforest loss during 1993–2005. Forest losses account for most reductions in aboveground carbon during the both time intervals, but Agroforest plays an increasingly important role in carbon reductions during the more recent interval. These results provide motivation for future REDD policies to count carbon changes associated with all influential land categories, such as Agroforests.

Keywords Agroforest · Carbon · Indonesia · Intensity analysis · Land-cover change · REDD

Introduction

Land change

The most important form of land conversion is the expansion of crops and pasture in natural ecosystems (Lambin and Meyfroidt 2011). The main driver of deforestation in Indonesia is agricultural expansion, such as transitions to rubber and oil palm (Miyamoto 2006, 2007). The rampant deforestation on the island of Sumatra was 12 million ha during 1985–2007 (Laumonier et al. 2010). Indonesia has been reported as one of the main contributors of greenhouse gases from deforestation and forest degradation (Baumert et al. 2004; Achard et al. 2004; Parker 2011).

If we are to understand and mitigate the possible negative impacts caused by land change, then it is essential to detect the patterns of land change, so that we can better grasp the processes of land change. Lambin (1997) points out that research concerning land change should be aimed at addressing the questions of why, where, and when? This paper answers the following questions: (1) During which time intervals is annual change area relatively slow versus fast? (2) Which land categories are relatively dormant versus active during a given time interval, and is the pattern stationary across time intervals? (3) Which transitions are targeting versus avoiding during a given time interval, and is the pattern stationary across time intervals? Simultaneously, we estimate carbon-stock change resulting from land-cover change to provide insights and recommendations for ongoing policy discussions concerning Indonesia's participation in reducing emissions from deforestation and degradation (REDD).

Sumatra's landscape history

The Dutch introduced rubber trees (*Hevea brasiliensis*) to Indonesia from Brazil at the beginning of the twentieth century. The climate of Sumatra is similar to the climate of Brazil, so these trees thrived and rapidly replaced shifting cultivation on the island (Gouyon et al. 1993). Forests transitioned to Agroforests, facilitated through policies that

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assigned property rights where rubber trees had been planted (Murdiyarso et al. 2002; van Noordwijk et al. 2012). The rubber boom during the 1920s influenced Sumatra's landscape as people planted more trees. Labor availability has been the primary constraint in rubber production, and the labor force has increased due to migrant labor from the Kerinci Mountains and Java during periods of high rubber prices (Suyanto et al. 2001).

Sumatra changed substantially during the 1970s, when the government began logging as a commercial activity, completed the Trans-Sumatran highway, and brought in a transmigrant population mostly from Java. Large-scale oil palm plantations followed during the 1990s. Van Noordwijk et al. (2012) and Tomich et al. (1998) describe the land-use change during the early 1990s, which saw the end of commercial logging and the beginning of a shift in production from food crops to rubber and oil palm. Sumatra had 4.4 million ha of oil palm in 2006 (van Noordwijk et al. 2008; IPOC 2006).

The REDD+ policy in Indonesia

Indonesia is the world's third largest greenhouse gas emitter (Metz 2007), and the country has the second highest rate of deforestation among tropical countries (Margono et al. 2012). Approximately, 80 % of the emissions are from deforestation and peat swamp degradation. The Government of Indonesia has declared its commitment to reduce by 2020 its baseline emissions by 26 % unilaterally and further by 15 % with international support.[1] Currently, the country is developing the REDD+ policy, but has problems to define a forest. If forests include tree plantations, then carbon finance could subsidize the transition from forests and woodlands to industrial timber and oil palm plantations (van Noordwijk and Minang 2009).

Jambi Province ranked 5th among the 30 provinces in Indonesia in terms of carbon dioxide emissions during 1990–2005, when Jambi emitted 0.5 Gt CO_2 equivalent per year, which amounted to 5 % of Indonesia's annual emissions (Ekadinata and Dewi 2011). Furthermore, 14 % of emissions were due to transition from agroforests to cropland, while 15 % were due to transition from undisturbed forest to cropland.

Our analysis provides decision support for the ongoing REDD+ discussions. We argue that the REDD+ policy should include agroforestry systems and community-based forests (Villamor 2012; Akiefnawati et al. 2010). Our paper also explores the processes of change at the local level, so we may identify appropriate actions at the local level.

[1] Intervention speech by H.E. Susilo Bambang Yudhoyono president of the republic of Indonesia on climate change presented at the 2009's G-20 Leaders Summit in Pittsburgh, USA.

Study area

Our study area covers approximately 16 thousand ha in Bungo district, Jambi province, Sumatra, Indonesia. The study area includes the villages of Laman Panjan, Lubuk Beringin, and Buat. The terrain is flat to undulating, with elevations ranging from 110 to 1,316 m above sea level. Lowland forests and mixed rubber agroforests once dominated the area (van Noordwijk et al. 2012). A part of the Kerinci Seblat National Park is upstream where farmers practice rain-fed rice cultivation; 550 households practice intensive rice cultivation along rivers downstream. Approximately 12 km separate the study area from Muara Bungo, which is the Bungo district capital.

The Bungo district had rubber plantations on 91 thousand ha and oil palm plantations on 48 thousand ha in 2006 (Bungo Statistics 2007). Rubber latex is the main crop. Fruits, such as durian (*Durio zibethinus*), duku (*Lansium domesticum*), rambutan (*Nephelium lappaceum*), and cinnamon (*Cinnamomum burmani*) are also common. The majority of the people are rubber tappers.

Lubuk Beringin is piloting a REDD scheme through the *hutan desa* agreement. *Hutan desa* means village forest, which is a mechanism awarded by the Minister of Forestry (P.49/Menhut-II/2008). Under this government mechanism, management of forested area includes responsibilities to preserve the life-supporting functions of the forests by giving rights to manage at village level. Thus, this *hutan desa* agreement serves as an essential precursor for REDD schemes by recognizing the villagers' right to manage the forest. The Indonesian government awarded the first *hutan desa* agreement to Lubuk Beringin mediated by the Warung Konservasi (WARSI), which is a local NGO and the World Agroforestry Center (ICRAF), which is an international research organization (Akiefnawati et al. 2010). The awarded *hutan desa* covers a total of 2,390 ha or 84 % of Lubuk Beringin's territory, and efforts to replicate the mechanism have been started in the neighboring villages.

Methodology

Data

Figure 1 shows maps of the study area for 1973, 1993, and 2005, which derive from Landsat MSS, Landsat TM, and Landsat ETM images. Our maps are a subset of the maps by Ekadinata and Vincent (2011), which come from Landscape Mosaic Project of ICRAF. Table 1 defines our maps' five land categories: Forest, Agroforest, Rubber, Palm and Others. All maps have a 30 m × 30 m resolution. We have partial information concerning the accuracy

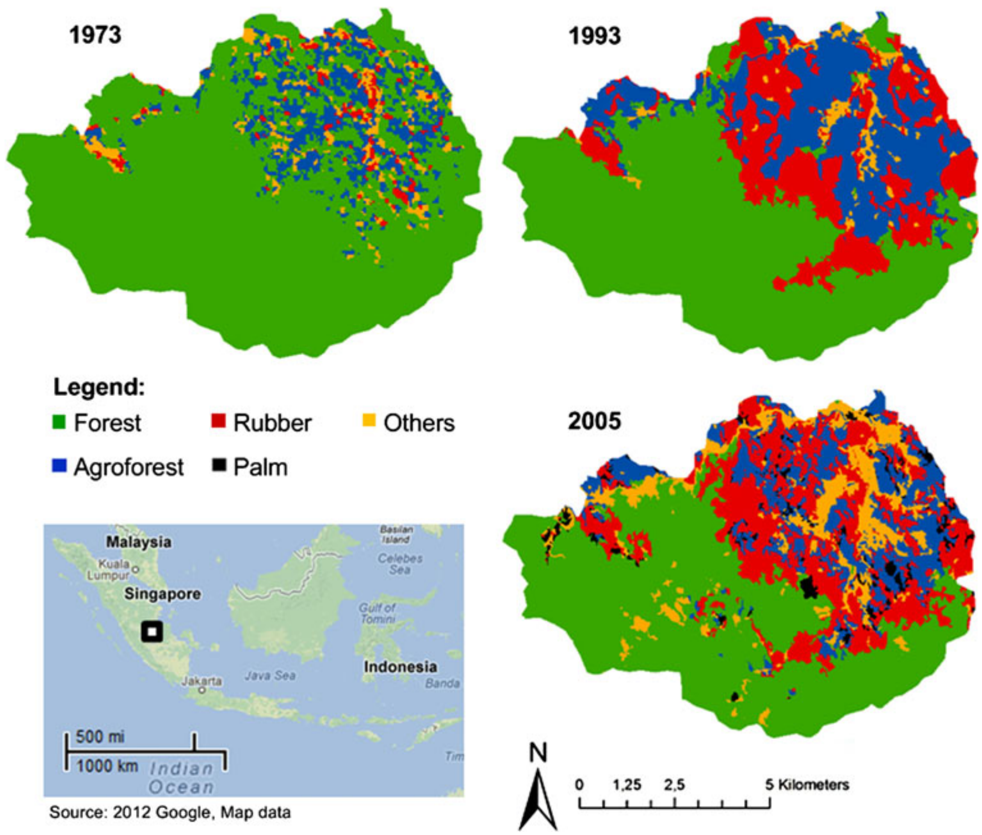

Fig. 1 Study area in Bungo district, Jambi Province (Sumatra), Indonesia. The *black square* in the *inset map* shows the location of Bungo district within Indonesia

Table 1 Definitions of land categories

Forest consists of dense and extensive tree cover usually consisting of stands varying in species, structure, composition age, and degree of logging. Forest excludes industrial tree plantations. Most Forests existed at greater than 500 m above sea level and had only small patches in the lowland peneplains as of 2002. Our Forest category is the Forest category of Ekadinata and Vincent (2011). We estimate the carbon density of this Forest category at 150 Mg/Ha (Tomich et al. 2001)
Agroforest consists mainly of rubber trees mixed with other tree species, forming a stand structure similar to secondary forest. Agroforest is also called *jungle rubber* because of the presence of wild woody species, which help to protect the rubber trees from weeds (Gouyon et al. 1993). Our Agroforest category is the Rubber Agroforest category of Ekadinata and Vincent (2011). We estimate the carbon density of this Agroforest category at 62 Mg/Ha (Tomich et al. 2001; Palm et al. 2004)
Rubber consists of intensively managed single species of rubber trees, such as plantations. Rubber also includes smallholdings, less intensively managed, and mixed with non-tree species such as shrubs. Our Rubber category is the Rubber Monoculture category of Ekadinata and Vincent (2011). We estimate the carbon density of this Rubber category at 46 Mg/Ha (Tomich et al. 2001)
Palm consists of oil palm as a single dominant species, usually managed intensively. Our Palm category is the Oil Palm category of Ekadinata and Vincent (2011). We estimate the carbon density of this Palm category at 31 Mg/Ha (Tomich et al. 2001)
Others consists of a mix of categories including shrublands, which consist of woody herbs, grasses, and non-woody herbs, in usually newly opened areas, which constitute the first phase of land conversion into rubber or oil palm plantations. Others also include residential, water, and rice fields that are mostly non-irrigated. Our Others category is the union of Ricefield, Shrub, Settlement, Water body, and Cloud and shadow of Ekadinata and Vincent (2011). We estimate the carbon density of this Others category at 31 Mg/Ha (Rahayu et al. 2005)

of the 2005 map, because Ekadinata and Vincent (2011) published a table concerning accuracy assessment for their 2005 map. We estimate the accuracy of our 2005 map at 96 %, after we aggregated some categories to create the Others category. We lack information concerning the accuracy of our other two maps. We suspect the accuracy of the 1973 and 1993 maps is similar to the accuracy of the 2005 map, because all the maps derive from similar technologies.

Intensity analysis

Intensity analysis is a mathematical framework that compares a uniform intensity versus observed intensities of temporal changes among categories (Aldwaik and Pontius 2012). Applications span six continents: Africa (Alo and Pontius 2008), Asia (Huang et al. 2012), Australia (Manandhar et al. 2010), Europe (Pérez-Hugalde et al. 2011), North America (Pontius et al. 2004), and South America

Table 2 Mathematical notation

T	Number of time points, which equals 3 for our case study
Y_t	Year at time point t
t	Index for the initial time point of interval $[Y_t, Y_{t+1}]$, where t ranges from 1 to $T-1$
J	Number of categories
i	Index for a category at an interval's initial time point
j	Index for a category at an interval's final time point
m	Index for the losing category for the selected transition
n	Index for the gaining category for the selected transition
C_{tij}	Number of pixels that transition from category i to category j during interval $[Y_t, Y_{t+1}]$
S_t	Annual change during interval $[Y_t, Y_{t+1}]$
U	Uniform annual change during extent $[Y_1, Y_3]$
G_{tj}	Intensity of annual gain of category j during interval $[Y_t, Y_{t+1}]$ relative to size of category j at time $t+1$
L_{ti}	Intensity of annual loss of category i during interval $[Y_t, Y_{t+1}]$ relative to size of category i at time t
R_{tin}	Intensity of annual transition from category i to category n during interval $[Y_t, Y_{t+1}]$ relative to size of category i at time t where $i \neq n$
W_{tn}	Uniform intensity of annual transition from all non-n categories to category n during interval $[Y_t, Y_{t+1}]$ relative to size of all non-n categories at time t
Q_{tmj}	Intensity of annual transition from category m to category j during interval $[Y_t, Y_{t+1}]$ relative to size of category j at time $t+1$ where $j \neq m$
V_{tm}	Uniform intensity of annual transition from all non-m categories to category j during interval $[Y_t, Y_{t+1}]$ relative to size of all non-m categories at time $t+1$
A_{ti}	Net change in aboveground carbon in the study area associated with gross losses of category i during time interval $[Y_t, Y_{t+1}]$ measured in gigagrams of carbon per year
D_i	Aboveground carbon density of category i measured in megagrams of carbon per hectare
B	Constant to convert A_{ti} to gigagrams of carbon per year
Δ_t	Net change in aboveground carbon in the study area during time interval $[Y_t, Y_{t+1}]$ measured in gigagrams of carbon per year

(Romero-Ruiz et al. 2011). We apply intensity analysis at three increasingly detailed levels: interval, category, and transition. Table 2 gives the notation that the equations use.

The interval level examines how the size of change during each time interval varies with respect to the duration of the interval. Equation 1 gives the uniform intensity U across the time extent $[Y_1, Y_T]$, where the study area is identical for all the time points. Equation 2 gives the annual change S_t during each interval $[Y_t, Y_{t+1}]$. If $S_t > U$, then the change is fast for $[Y_t, Y_{t+1}]$; if $S_t < U$, then the change is slow for $[Y_t, Y_{t+1}]$; and if $S_t = U$ for all the time intervals, then the annual change is stationary. We separate the change during each interval into two parts: quantity and allocation (Pontius and Millones 2011). Quantity change is the subset of change during an interval that is due to the difference between the quantity of a category at Y_t and the quantity of the same category at Y_{t+1}. For example, if Forest loss does not equal to Forest gain during an interval, then the Forest produces some quantity change during that interval. Allocation change is the subset of change during an interval that is due to less than maximum match in the allocation of the categories, given the quantity of each category at Y_t and Y_{t+1}. For example, if Agroforest experiences both gain and loss during an interval, then Agroforest produces some allocation change during that interval. Equation 3 gives the annual quantity change during interval $[Y_t, Y_{t+1}]$. Equation 4 gives the annual allocation change during interval $[Y_t, Y_{t+1}]$.

$$U = \frac{(\text{change area during all intervals})\ 100\,\%}{(\text{duration of all intervals})\ \text{domain area}} = \frac{\sum_{t=1}^{T-1}\left\{\sum_{j=1}^{J}\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right]\right\} 100\,\%}{(Y_T - Y_1)\sum_{j=1}^{J}\sum_{i=1}^{J} C_{1ij}} \quad (1)$$

$$S_t = \frac{(\text{change area during } [Y_{t+1}, Y_t])\ 100\,\%}{(\text{duration of } [Y_{t+1}, Y_t])\ \text{domain area}} = \frac{\sum_{j=1}^{J}\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right] 100\,\%}{(Y_{t+1} - Y_t)\sum_{j=1}^{J}\sum_{i=1}^{J} C_{tij}} \quad (2)$$

$$\text{Annual quantity change during } [Y_{t+1}, Y_t] = \frac{\sum_{j=1}^{J}\left[\sum_{i=1}^{J}\left(C_{tij} - C_{tji}\right)\right] 100\,\%}{2(Y_{t+1} - Y_t)\sum_{j=1}^{J}\sum_{i=1}^{J} C_{tij}} \quad (3)$$

$$\text{Annual allocation change during } [Y_{t+1}, Y_t] = S_t - \text{Annual quantity change during } [Y_{t+1}, Y_t] \quad (4)$$

The category level examines how the categories' gains and losses during an interval vary with respect to the sizes of those categories. Equation 5 gives the gain intensity of category j during $[Y_t, Y_{t+1}]$. Equation 6 gives the loss intensity of category i during $[Y_t, Y_{t+1}]$. We compare the observed categorical intensities to the uniform intensity of annual change S_t that would occur if the change during each interval were allocated uniformly across the study area. If the category intensity is greater than S_t, then the category is active during that interval. If the category intensity is less than S_t, then the category is dormant during that interval. If the category's gain and loss are allocated uniformly in the study area, then that category's G_{tj} and L_{ti} would equal to S_t.

$$G_{tj} = \frac{(\text{area of gain of } j \text{ during } [Y_t, Y_{t+1}])\ 100\,\%}{(\text{duration of } [Y_t, Y_{t+1}])\ \text{area of } j \text{ at } Y_{t+1}} = \frac{\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right] 100\,\%}{(Y_{t+1} - Y_t)\sum_{i=1}^{J} C_{tij}} \tag{5}$$

$$L_{ti} = \frac{(\text{area of loss of } i \text{ during } [Y_t, Y_{t+1}])\ 100\,\%}{(\text{duration of } [Y_t, Y_{t+1}])\ \text{area of } i \text{ at } Y_t} = \frac{\left[\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tii}\right] 100\,\%}{(Y_{t+1} - Y_t)\sum_{j=1}^{J} C_{tij}} \tag{6}$$

The transition level examines how the sizes of transitions during an interval vary with respect to the size of the categories available for those transitions. Equation 7 computes the uniform transition intensity for the gain of category n from all non-n categories during $[Y_t, Y_{t+1}]$. Equation 8 computes the observed intensity of the transition from i to n during $[Y_t, Y_{t+1}]$. If a transition's observed intensity is greater than the corresponding uniform intensity, then the category targets the particular transition. If a transition's observed intensity is less than the corresponding uniform intensity, then the category avoids the particular transition. Equations 7 and 8 analyze transitions with respect to the gain of category n. Equations 9 and 10 analyze transitions with respect to the loss of category m. Equation 9 computes the uniform transition intensity for the loss of category m from all non-m categories during $[Y_t, Y_{t+1}]$. Equation 10 computes the observed intensity of the transition from m to j during $[Y_t, Y_{t+1}]$.

$$W_{tn} = \frac{(\text{area of gain to } n \text{ during } [Y_t, Y_{t+1}])\ 100\,\%}{(\text{duration of } [Y_t, Y_{t+1}])\ \text{area of non-}n \text{ at } Y_t} = \frac{\left[\left(\sum_{i=1}^{J} C_{tin}\right) - C_{tnn}\right] 100\,\%}{(Y_{t+1} - Y_t)\sum_{j=1}^{J}\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tnj}\right]} \tag{7}$$

$$R_{tin} = \frac{(\text{area of transition from } i \text{ to } n \text{ during } [Y_t, Y_{t+1}])\ 100\,\%}{(\text{duration of } [Y_t, Y_{t+1}])\ \text{area of } i \text{ at } Y_t} = \frac{C_{tin}\,100\,\%}{(Y_{t+1} - Y_t)\sum_{j=1}^{J} C_{tij}} \tag{8}$$

$$V_{tm} = \frac{(\text{area of loss from } m \text{ during } [Y_t, Y_{t+1}])\ 100\,\%}{(\text{duration of } [Y_t, Y_{t+1}])\ \text{area of non-}m \text{ at } Y_{t+1}} = \frac{\left[\left(\sum_{j=1}^{J} C_{tmj}\right) - C_{tmm}\right] 100\,\%}{(Y_{t+1} - Y_t)\sum_{i=1}^{J}\left[\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tim}\right]} \tag{9}$$

$$Q_{tmj} = \frac{(\text{area of transition from } m \text{ to } j \text{ during } [Y_t, Y_{t+1}])\ 100\,\%}{(\text{duration of } [Y_t, Y_{t+1}])\ \text{area of } j \text{ at } Y_{t+1}} = \frac{C_{tmj}\,100\,\%}{(Y_{t+1} - Y_t)\sum_{i=1}^{J} C_{tij}} \tag{10}$$

Carbon-stock change estimation

We estimate carbon-stock changes during each of the time interval by using two types of information: carbon density by land category (D_i) and area of transitions between land categories (C_{tij}). Equation 11 computes annual change in carbon stock for the gross loss of each category i, and then, Eq. 12 sums all categories to attain the annual net change of carbon stock during interval $[Y_t, Y_{t+1}]$. Table 2 gives the mathematical notation.

$$A_{ti} = \frac{\text{sum of carbon change due to transitions from } i}{\text{duration of } [Y_{t+1}, Y_t]} = \frac{B\sum_{j=1}^{J} C_{tij}(D_j - D_i)}{Y_{t+1} - Y_t} \tag{11}$$

$$\Delta_t = \sum_{i=1}^{J} A_{ti} \tag{12}$$

Results

Intensity analysis

Figure 2 shows that the annual area change during 1993–2005 is faster than the annual area change during 1973–1993. Only 23 % of the total change is allocation change during the first interval when most change was Forest loss, and then, 47 % of the total change is allocation change during the second interval when both Agroforest and Rubber simultaneously gained and lost.

Figure 3 indicates that Forest accounted for 73 % of all area losses during 1973–1993. During 1993–2005, Forest accounted for only 26 % of all losses, while Agroforest accounted for 45 % and Rubber accounted for 26 %. Agroforest showed net gain during 1973–1993 and then showed net loss during 1993–2005. Palm became a new category during 1993–2005. Figure 4 shows that Agroforest and Rubber are active during both time intervals, and that Agroforest loses more intensively than Forest loses.

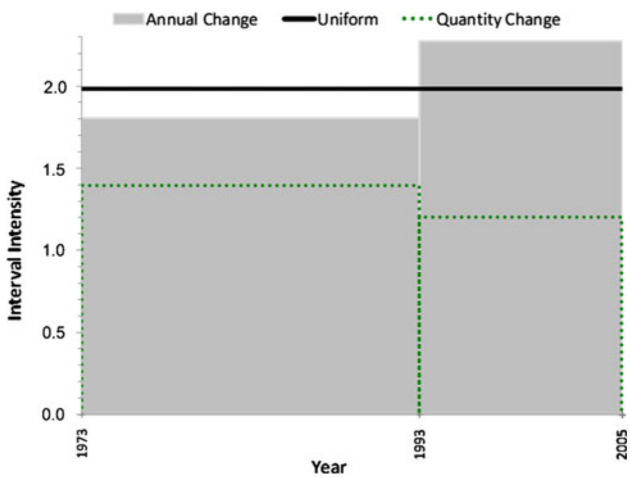

Fig. 2 Interval level change intensity as an annual percent of the study area. The *dotted line* encloses quantity change. Allocation change is the change above the *dotted line*

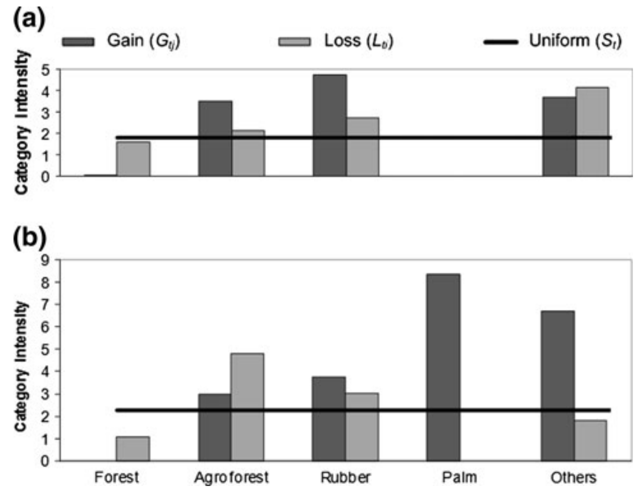

Fig. 4 Category level gain and loss intensities during **a** 1973–1993 and **b** 1993–2005. Units are annual percent of the category at the latter time of the interval for gains and at the initial time of the interval for losses. If a *bar* extends above the uniform intensity line, then the category is active. If a *bar* stops below the uniform intensity line, then the category is dormant

Figure 5a shows that Rubber targets Forest's loss during 1973–1993, and Fig. 5b shows both Palm and Others target Forest's loss during 1993–2005. Agroforest avoids Forest's loss during the latter interval. Figure 5c, d shows that Rubber and Others target Agroforest's loss during both intervals. Figure 5c, d shows also that Agroforest's gain targets Rubber during both intervals, and that Agroforest's gain avoids Forest during the latter interval.

The transition from category i to category j is a *systematically targeting transition* when the gain of j targets i, while j targets the loss of i, i.e., $R_{tij} > W_{tj}$ while $Q_{tij} > V_{ti}$. The transition from category i to category j is a *systematically avoiding transition* when the gain of j avoids i, while j avoids the loss of i, i.e., $R_{tij} < W_{tj}$ while $Q_{tij} < V_{ti}$. Table 3 shows eleven transitions are systematically targeting transitions, none of which involve Forest. Table 3 shows seven transitions are systematically avoiding transitions, all of which involve Forest or Agroforest. If a transition is systematic in the same direction during consecutive time intervals, then the transition is stationary across those time intervals. Three systematically targeting transitions are stationary: from Agroforest to Others, from Rubber to Agroforest, and from Rubber to Others. The only systematically avoiding stationary transition is from Forest to Agroforest.

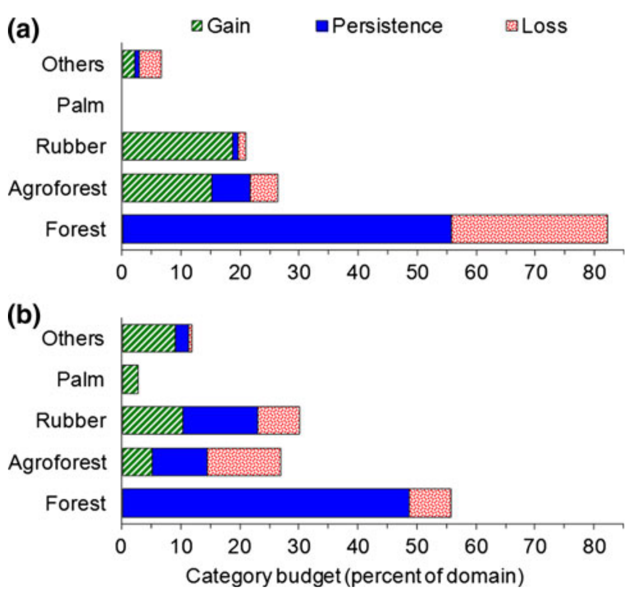

Fig. 3 Gains, persistence, and losses during **a** 1973–1993 and **b** 1993–2005

Carbon-stock changes

Figure 6 shows annual net aboveground carbon loss of 20 Gg per year during the first time interval, and then 13 Gg per year during the second interval. Carbon losses were mostly due to Forest loss during both intervals; however, Agroforest accounts for an increasing portion of carbon losses from the first to the second time intervals.

Land-cover change was faster, and net carbon loss was slower during the latter interval. Tables 1 and 3 explain how this occurs. Table 3 shows that Forest loss accounts for the plurality of area loss during the former interval; then, Agroforest accounts for the plurality of area loss during the latter interval. This information combines with the information from Table 1 that Forest has a higher carbon density than Agroforest. Thus, land-cover change is accelerating, while carbon loss is decelerating, as land dynamics shift from Forest loss to Agroforest loss.

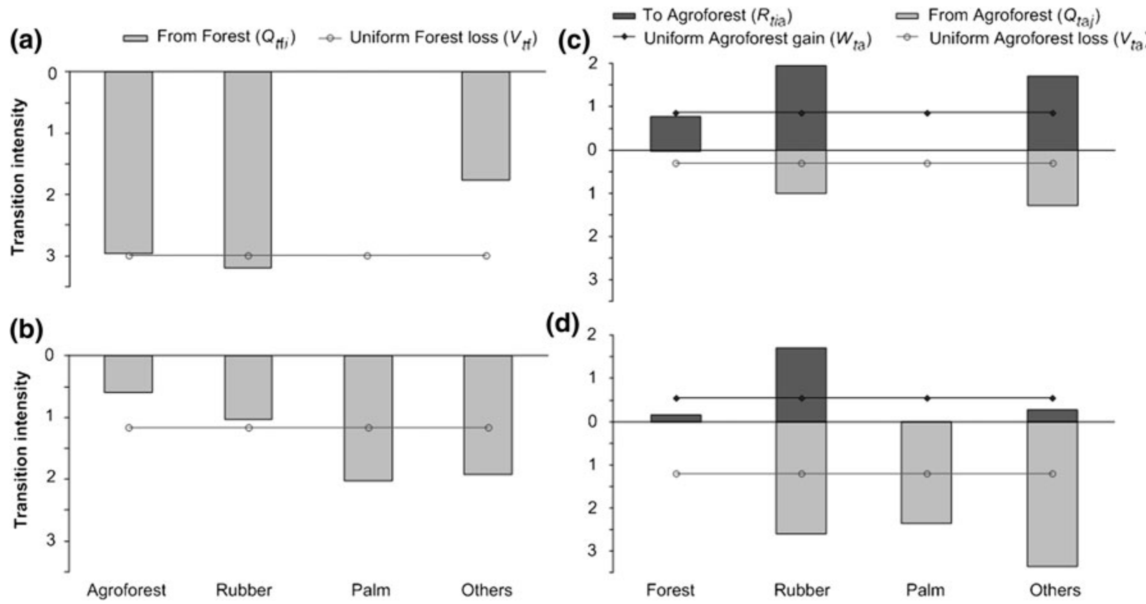

Fig. 5 Transition level intensities for Forest during **a** 1973–1993 and **b** 1993–2005 and for Agroforest during **c** 1973–1993 and **d** 1993–2005. Units are annual percent of the non-Forest category at the latter time point for **a** and **b**. Units are annual percent of the non-Agroforest category for **c** and **d**. If a *bar* extends beyond the uniform intensity line, then its category targets. If a *bar* stops short of the line, then its category avoids. *Subscript f* refers to Forest, and *subscript a* refers to Agroforest

Table 3 Annual square kilometers of each transition in the form of a flow matrix (Runfola and Pontius 2013)

	To					
From	Forest	Agroforest	Rubber	Palm	Others	Total loss
Forest		101^{α}, 14^{α}	99, 37^{α}	0, 9	8^{α}, 34	208, 94
Agroforest	1^{α}, 0		31, 94^{τ}	0, 10^{τ}	6^{τ}, 59^{τ}	37, 163
Rubber	0^{α}, 0	7^{τ}, 53^{τ}		0, 16^{τ}	3^{τ}, 25^{τ}	10, 93
Palm	0, 0	0, 0	0, 0		0, 0	0, 0
Others	1, 0	12, 1^{α}	17, 6^{τ}	0, 2^{τ}		29, 8
Total gain	1, 0	120, 68	147, 136	0, 36	16, 118	284, 358

The number before the comma is during 1973–1993, and the number after the comma is during 1993–2005. A superscript of τ indicates a systematically targeting transition. A superscript of α indicates a systematically avoiding transition

Fig. 6 Annual net change in aboveground carbon during 1973–1993 and 1993–2005

Discussion

Land-cover change and socioeconomic processes

Ekadinata and Vincent (2011) report three trends in percent of the entire Bungo district from 1973 to 2005: (1) decrease in Forest from 75 to 30, (2) decrease in agroforest from 15 to 11, and (3) increase in Rubber from 2 to 27. Our study of a sub-region of Bungo district compliments their study because our study (1) quantifies the acceleration of land-cover change during sequential time intervals, (2) identifies the land categories that are active or dormant regarding gains and losses, and (3) identifies systematically targeting and avoiding transitions.

Annual land-cover change has accelerated (Fig. 2). A likely driver is the doubling of oil palm prices and a quadrupling of rubber prices during 1995–1998 (Penot 2004), which made it profitable for farmers to convert their complex agroforests into a monoculture system (Martini et al. 2010). Palm emerged during the latter time interval, and Rubber accounted for the plurality of gains during both time intervals (Fig. 3). A combination of political, social, and economic events encouraged changes in farming systems and land use (Geissler and Penot 2000; Penot 2004). Transitions from Agroforest became larger and more intense during the latter interval (Figs. 3, 4, 5; Table 3). Transitions to Rubber became systematic during

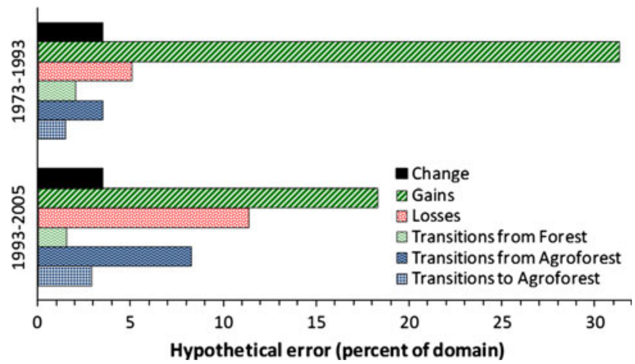

Fig. 7 Hypothetical errors that could account for deviations from uniform change. Change in the legend refers to error in the map of change versus persistence during the interval. Gains refer to error in the map at the latter time point of the interval. Losses refer to error in the map at the initial time point of the interval. Transitions from a category refer to error in the map at the initial time point of the interval. Transitions to Agroforest refer to error in the map at the latter time point of the interval

1993–2005, when Rubber targeted both Agroforest and Others, while Rubber avoided Forest (Table 3).

Map error

It is impossible to know with certainty whether map error could account for deviations between observed and uniform intensities, because we do not know the accuracy of the maps precisely. However, Aldwaik and Pontius (2013) offer a method to consider the effect of hypothetical map error exactly for this situation. Their equations compute the size and types of hypothetical map errors that could account for observed deviations from a uniform intensity of change, at each level of intensity analysis. Larger hypothetical errors indicate stronger evidence that the real changes are nonuniform.

Figure 7 shows the minimum hypothetical map errors that could account for deviations between observed changes and uniform change. Hypothetical error concerning change versus persistence in 4 % of the study area could account for the earlier interval appearing slower than the latter interval (Fig. 2). Errors in 11 % of the study area at 1993 could account for deviations from uniform losses during 1993–2005 (Fig. 4b). Errors in 8 % of the study area at 1993 could account for deviations from uniform transitions from Agroforest during 1993–2005 (Fig. 5d).

Carbon-stock change and REDD

Ekadinata and Dewi (2011) used land-use and land-cover maps with 30 m × 30 m grids and local-based carbon emission factor to estimate that annual emissions due to land-cover change for the whole of Indonesia. Their results show annual emissions decelerated from 0.79 Gt CO_2 equivalent per year during 1990–2000 to 0.47 Gt CO_2 equivalent per year during 2000–2005. Our Fig. 6 shows a similar deceleration, as net loss of aboveground carbon slowed from 20 Gg per year during 1973–1993 to 13 Gg per year during 1993–2005. In spite of this deceleration, Indonesia remains one of the largest carbon emitters through deforestation and degradation. Thus, emissions from carbon-dense forests and agroforests warrant urgent attention.

REDD policies can have a profound influence on conservation, sustainable management, and enhancement of carbon stocks in developing countries. Thus, REDD policies should recognize the role of non-forest categories such as Agroforests in the context of Indonesia. If policies count only Forest, then accounts will miss carbon changes due to transitions with Agroforests. The province of Jambi is aiming to pioneer the REDD scheme; thus, the REDD scheme must consider information on the drivers, dynamics, and processes of land changes, including deforestation beyond the forest sector. The REDD scheme will fail unless it considers non-forest sectors (van Noordwijk and Minang 2009; Minang et al. 2012).

Conclusions

Annual area of land-cover change during 1993–2005 is faster than during 1973–1993. Historical evidence explains this finding, since there were increasing resource pressures, changing market opportunities, and intervening outside policies during 1993–2005. Agroforest and Rubber actively changed for both gains and losses during both intervals. Palm emerged during 1993–2005. The largest transition during 1993–2005 is from Agroforest to Rubber, which is a systematically targeting transition that is important because the carbon density of Agroforest is greater than that of Rubber. Forest accounted for nearly all land transitions during the earlier time interval, and Forest has more than twice the carbon density of any other category. Agroforest accounts for a larger area of land-cover change than Forest during the latter time interval, while the carbon density of Agroforest ranks second behind Forest. Consequently, the annual reduction in aboveground carbon is decelerating because Agroforest plays an increasingly important role in total net aboveground carbon reduction during the more recent time interval. Therefore, REDD policies should account for Agroforest's role in carbon budgets.

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