EVALUATION OF CARBON SEQUESTRATION AMOUNT AND BASELINE USING SATELLITE IMAGERY IN ARID LAND

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KEY WORDS: *Acacia aneura*, Afforestation, CDM/JI, *Eucalyptus camaldulensis*, LANDSAT, Western Australia

ABSTRACT:

As a countermeasure to the greenhouse effect, afforestation in arid areas has been proposed and tested in an arid area of Western Australia. According to the CDM/JI guidelines set by UNFCCC, the sequestrated carbon amount accountable as carbon credit was estimated in this study. First, the sequestrated carbon amount by planted trees was measured by repeated tree censuses. Second, the land use type (vegetation type) was estimated using LANDSAT images by a statistical method. Of all the images, the Khat statistics were over 0.8, and the overall accuracy was over 80%. Third, by repeated tree censuses, the mean annual increment (MAI) at natural vegetation monitoring sites of each vegetation type was calculated, and this MAI data were used as the baseline of each vegetation. Fourth, the present biomass distribution was estimated using the SAVI index, since the original vegetation must be clear-cut before an afforestation area can be established. Fifth, the sequestrated carbon amount accountable as carbon credit was estimated inside a 45×50 km area. The results of this study indicated that afforestation areas should be established in the order corresponding to “bare ground”, “*Acacia* woodland” and “vegetation transition area” and that total accountable carbon credit was from 2,955 to 3,770 Gg-CO_2 in around 170,000 to 190,000 ha of the research area.

1. INTRODUCTION

As countermeasures against the greenhouse effect, two types of methods can be used. One is emission reduction, and the other is Greenhouse Gas (GHG) capture. Typical examples of emission reduction are improving energy-saving technology and renewable energy development, and those of GHG capture are Carbon Capture and Storage (CCS) and afforestation. Our research team focused on afforestation in arid areas as a GHG capture method and has been studying an arid area of Western Australia (Yamada *et al*., 2003).

In our research area, afforestation test sites were established in 1999 and have been monitored at regular intervals. The results of our research suggest that, through the application of the water-harvesting method and the hardpan blasting method (Yamada *et al*., 2003), some *Eucalyptus* species, especially *Eucalyptus camaldulensis*, have been able to survive in this arid area. Then, using the afforestation method of Yamada *et al*. (2003), large-scale afforestation can be established inside our research area.

To evaluate the sequestrated carbon amount by this large-scale afforestation method as carbon credit (accountable carbon amount), a guideline determined by UNFCCC (2006) must be adopted. For Clean Development Mechanism/Joint Implementation (CDM/JI) afforestation, the accountable carbon amount should be calculated as the “actual net GHG removals by sinks” minus the “baseline net GHG removals by sinks” minus “leakage” in five carbon pools. Of these five carbon pools, the above-ground biomass and below-ground biomass will change rapidly after afforestation.

In this study, as the first step, the changes in these 2 types of carbon pools were estimated using ground truth and remote-sensing techniques, and the accountable carbon amount was evaluated according to the guidelines of UNFCCC (2006).

2. MATERIALS AND METHODS

2.1 Research area

The research area of this study is Sturt Meadows (28˚40'S, 120˚58'E) near Leonora, located about 600 km from Perth, the provincial capital of Western Australia. The range of our research area is approximately 45 km east and west and 50 km north and south. This research site belongs to the Murchison region of Interim Biogeographic Regionalization of Australia (IBRA) Version 5.1 (Environment Australia, 2000). The mean annual rainfall is about 200 mm, thus this area is categorized as an arid area (Yasuda *et al*., 2001). The Murchison environment was described as having Mulga (*Acacia aneura*) low woodlands, often rich in ephemerals, on outcrop hardpan wash plains and fine-textured quaternary alluvial and eluvial surfaces mantling granitic and greenstone strata (Environment Australia, 2000). From the vegetation classification results (Suganuma *et al*., 2006a), this research area is classified as having 5 types of vegetation, i.e., *Acacia* forest and woodland, *Eucalyptus* forest and woodland, bare ground, halophyte, and Hydrosol (salt lake).

2.2 MAI (Mean Annual Increment) measurement of the afforestation site

One of the afforestation test sites, the largest site, named site C, was used to determine the amount of carbon captured by planted trees each year. Site C consists of 16 subplots; 11 subplots were chosen for this study because they had been established by the same method. Each subplot has water-harvesting bank, and each tree was planted in a separate blasted hole because a very hard soil layer, called a “hardpan layer,” exists near the soil surface (Bettenay and Churchward, 1974). Ten tree species were planted in these 11 subplots, and the main species was *E. camaldulensis*. Detailed site information is provided in Shiono

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et al. (2007).

Repeated tree censuses have been carried out at site C, but, in this study, for simplification, the census data of 1999 and 2003 were used for biomass calculation (the latest census data had not been sorted yet). For biomass calculation, the allometric equations in Suganuma *et al*. (2006b) were used. From the difference between the biomass of 1999 and that of 2003, MAI (Mg ha^{-1}) in each subplot was calculated. The captured carbon amount was calculated from this MAI data.

2.3 Vegetation classification

Five different LANDSAT images (5 TM and 7 ETM+; path 100 /row 80) were used for vegetation classification. Each image was pre-processed by geometric correction, radiance conversion from the DN value, and atmospheric correction (dark pixel subtraction method). This was done using ERDAS IMAGINE 9.1.

Based on the ground truth information, the radiance distribution of each vegetation type was gathered from each image (over 4000 pixels). From this radiance distribution data, applying factor analysis and discriminant analysis, a decision tree was made and 5 vegetation types were classified in each image. The detailed classification method is described in Suganuma *et al*. (2006a).

Each classified image was checked by over 500 pints of data and error matrixes were made. According to the accuracy assessment method of Congalton and Green (1999), the Khat statistics and overall accuracy were calculated, and the significance of classification was tested in 5 images. In addition, the similarity of 5 classification results was also tested according to the assessment methods of Congalton and Green (1999).

After accuracy assessment, classification images that were not significantly different were overlaid, and a new classification image was made. This image consisted of 5 stable vegetation types (*Acacia* woodland, *Eucalyptus* woodland, bare ground, halophyte, and Hydrosol) and a vegetation transition area. The stable vegetation type was the area in which all classification images were reported to be the same vegetation type. If not all images were reported to be the same vegetation type for some area, the area was then classified as a vegetation transition area. Okin *et al*. (2001) reported that the classification results were not reliable in areas with low vegetation cover (under 30%) in arid and semiarid areas; thus, the classification results highly depended on satellite image conditions. Then, to avoid classification error, the stable vegetation and transition areas were divided in this study.

2.4 MAI measurement of each natural vegetation

From the classified areas, bare ground, Acacia woodland, and the vegetation transition area were candidates for afforestation; therefore, the baseline MAI data needed to be calculated in each vegetation type. From repeated tree censuses (from 1997 to 2007), the MAI (Mg ha^{-1}) was calculated in these tree types of vegetation, and these data were used as the "baseline net GHG removals by sinks."

2.5 Biomass distribution estimation

Since the afforestation method requires hardpan blasting and a water-harvesting bank, the original vegetation must be clear-cut before afforestation sites can be established. Thus, the original biomass was accounted as a minus value in the "actual net GHG removals by sinks." In this study, using LANDSAT 5 TM image (Nov/19th/1999), the biomass distribution at the time of establishing afforestation sites was estimated by the equation of SAVI (Huete, 1988) and biomass of research area (Mg ha^{-1}: Suganuma *et al*., 2006a). The coefficient of determination (R^2) of this equation was 0.95, and the Root Mean Squared Error (RMSE) was 6.2 Mg ha^{-1} (sample number = 18).

2.6 Evaluation of the carbon sequestration amount

According to the assessment method by UNFCCC (2006), the accountable carbon amount by afforestation in this research area was calculated using following equation.

$$AC = \{(MAI_A - MAI_B)\times N - B\} \times 0.5\times(44/12)\times Area \quad (1)$$

Where AC = accountable carbon (Mg-CO_2 ha^{-1})
MAI_A = MAI in afforestation sites (Mg ha^{-1} $year^{-1}$)
MAI_B = MAI in natural vegetation (Mg ha^{-1} $year^{-1}$)
N = afforestation length (year)
B = biomass for clear cut (Mg ha^{-1})
0.5 = carbon conversion factor from biomass
44/12 = CO_2 conversion factor from carbon
Area = afforestation applicable area

Because the original land use type is rough grazing, livestock must be isolated from the afforestation area but can move back to it after several years. Thus, in this study, "Leakage" was judged as zero. In addition, CO_2 emission when establishing the afforestation area (2.1 Mg-CO_2 ha^{-1}: Tahara *et al*., 2009) should be calculated as a minus value in the above equation, however, the establishment of a method of afforestation sites is now under investigation. Then, this value was neglected in this study. The afforestation length was set as 30 years in this study, since the growth of *Eucalyptus camaldulensis* was considered to stop after around 30 years (Suganuma *et al*., unpublished data). Using Equation (1), the afforestation applicable area and total accountable carbon amount (CO_2 conversion) were estimated for each original vegetation type.

3. RESULTS AND DISCUSSION

3.1 MAI measurement of the afforestation site

Sub-site number	Stand biomass [Mg ha^{-1}] 1st census (1999) Stem & Branch	Leaf	Root	2nd census (2003) Stem & Branch	Leaf	Root	Mean annual increment [Mg-CO_2 ha^{-1} $year^{-1}$]	Plot area [ha]	Stand density [n ha^{-1}]
1	0.13	0.07	0.11	4.26	0.88	3.17	3.60	0.24	173
2	0.16	0.08	0.13	3.91	0.80	3.05	3.33	0.24	177
3	0.16	0.08	0.14	3.01	0.70	2.31	2.53	0.20	197
4	0.12	0.06	0.10	4.09	0.79	3.08	3.45	0.22	194
6	0.16	0.09	0.14	6.96	1.16	5.35	5.88	0.19	226
7	0.17	0.08	0.15	4.29	0.79	3.31	3.60	0.21	196
8	0.07	0.05	0.07	3.87	0.81	3.07	3.40	0.19	212
9	0.12	0.07	0.11	7.53	1.18	5.69	6.34	0.17	248
10	0.11	0.06	0.10	5.44	0.94	4.02	4.56	0.22	194
11	0.17	0.09	0.15	4.74	0.91	3.54	3.95	0.23	205
12	0.09	0.05	0.08	4.24	0.76	3.26	3.62	0.23	213

Table 1. MAI of 11 subplots in the afforestation site.

As shown on Table 1, the average MAI was calculated as 4.02 Mg-CO_2 ha^{-1} $year^{-1}$, and the Standard Error (*S.E.*) was 0.33. The maximum and minimum MAI values are 6.34 and 2.53, respectively.

3.2 Vegetation classification

As shown on Table 2, the vegetation classification of 5 images was properly carried out. The Khat statistics of all images exceeded 0.8. The overall accuracy of all images, except that on July 27th, 2001, also exceeded 80%. Since the classification significance (Z_1) of all images exceeded 1.957, all the classifi-

Satellite image	LANDSAT 5 TM		LANDSAT7 ETM+		
Obtained date	1998/Dec./18	1999/Nov./19th	1999/Oct./26th	2001/Jul./27th	2002/Apr./9th
Overall accuracy (%)	84.4	88.4	86.3	83.0	87.0
Kappa Statistics	0.800	0.852	0.826	0.783	0.833
Var(Kappa)	0.000425	0.000316	0.000361	0.000418	0.000352
Sample number	508	528	527	534	523
$Z_1 = \frac{Kappa}{\sqrt{\mathrm{var}(Kappa)}}$	38.303	47.880	43.450	38.267	44.375
$Z_2 = \frac{\lvert Kappa_1 - Kappa_2 \rvert}{\sqrt{\mathrm{var}(Kappa_1) - \mathrm{var}(Kappa_2)}}$	1.902	—	1.005	2.546	0.724

Z_1(0.05, two-tailed) = Z_2 (0.05, two-tailed) = 1.957

Table 2. Summary of the accuracy assessment of satellite images.

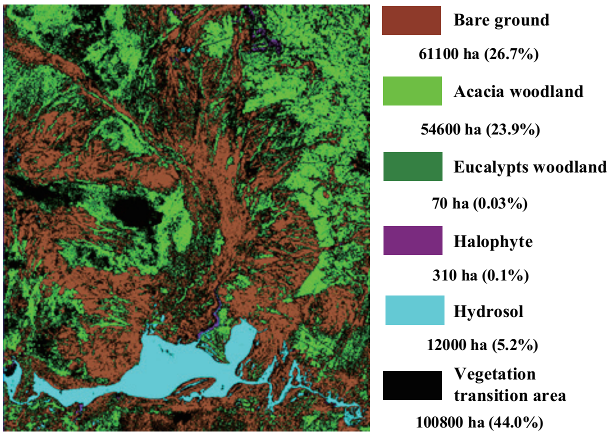

Figure 1. Stable vegetation and vegetation transition areas.

cation results were judged as significant. However, the classification results of July 27th, 2001 were judged as significantly different from others by the Z_2 value. Therefore, this image was not used for estimating the stable vegetation.
Five types of stable vegetation and vegetation transition areas were estimated by overlaying 4 classification results (Fig. 1). From this figure, most of the research area was occupied by Acacia woodland, bare ground, and the vegetation transition area. *Eucalyptus* woodland and hydrosol were less than or equal to 0.1%. About 95% of the research area was investigated to determine whether it was an afforestation candidate or not.

3.3 MAI measurement of each natural vegetation type

		Average	Standard error	Min.	Max	n
			[Mg-CO_2 ha^{-1} year^{-1}]			
Bare ground	A	0.104	0.076	-0.562	1.249	21
	B	0.196	0.084	0.005	1.249	16
Vegetation transition area	A	1.064	0.413	-6.143	12.089	58
	B	1.613	0.435	0.006	12.089	49
Acacia woodland	A	0.109	0.369	-12.204	7.968	68
	B	1.071	0.263	0.027	7.968	54

Table 3. Baseline data of each vegetation type.

As shown on Table 3, the average of the MAI, Standard Error (*S.E.*), and minimum and maximum MAI were calculated, and this data were used as the "baseline net GHG removals by sinks" (baseline). However, the MAI of natural vegetation contains minus values; therefore, when the baseline was calculated from all MAI values, the baseline absolute value became small, and then the accountable carbon amount became relatively large. To avoide overestimation, two types of baseline were then set. Baseline A was the average of the MAI calculated from all the MAI values. Baseline B was the average MAI calculated from the MAI excluding minus values.
For baseline A, the average MAI of *Acacia* woodland became similar to that of bare ground, and that of the vegetation transition area was about ten times larger than that of others. For baseline B, the average MAI data were in the order of the vegetation transition area, *Acacia* woodland, bare ground. Thus,

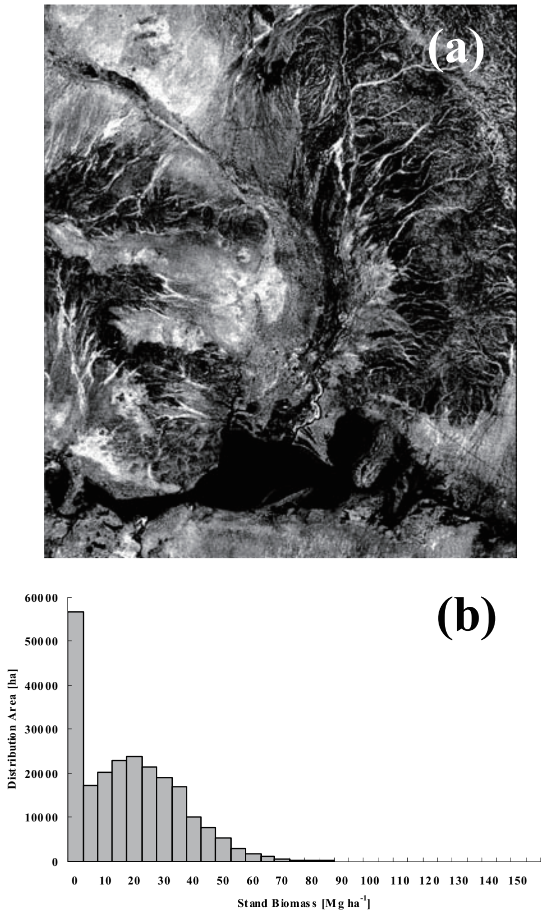

Figure 2. Biomass distribution of research area.

the average MAI of the vegetation transition area was larger than that of the stable vegetation area.

3.4 Biomass distribution estimation

The biomass distribution of natural vegetation was estimated as shown in Figure 2(a). This figure shows an area that is 45 km east and west and 50 km north and south. The black area corresponds to 0 Mg ha^{-1} biomass. The brightest area corresponds to 260 Mg ha^{-1}. However, the maximum biomass in this research area was observed to be 150 Mg ha^{-1}, suggesting that some areas had an overestimation. However, since less than 0.01% of the area had biomass exceeding 150 Mg ha^{-1}, these areas were considered to be negligible estimation errors.
Figure 2(b) shows the distribution area of each biomass class in 5 Mg ha^{-1} steps. As this research area is an arid area, most of the area has low biomass. Among the area with biomass of 0 Mg ha^{-1}, about 11,000 ha is salt lake (Hydrosol).
This estimated biomass distribution data was used as B in Equation (1).

3.5 Evaluation of carbon sequestration amount

From the Equation (1) and the above-mentioned results, the estimated accountable CO_2 amounts varied, as shown in Figures 3 and 4. Both figures show the accountable CO_2 amount, but the adopted baseline scenario differed. In both figures, the X axis shows the stand biomass class of original vegetation, and its upper limit shows that the value of accountable CO_2 exceeds zero. The Y axis shows the gross value of sequestrated carbon amount by planted trees. In these figures, "Accountable CO_2" corresponds to AC in Equation (1). "Clear cut biomass" and

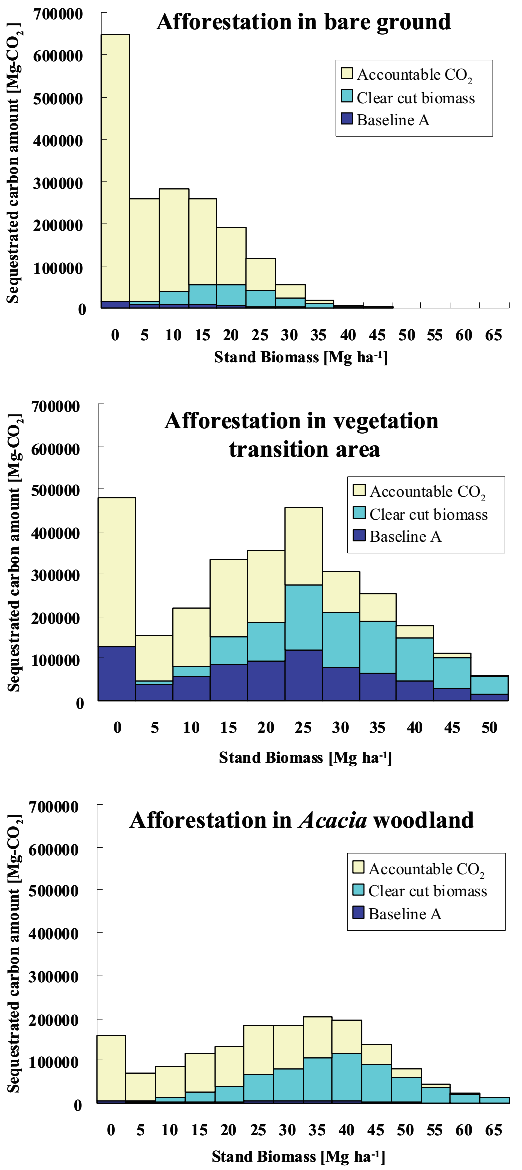

Figure 3. Sequestrated carbon amount by CO_2 conversion when afforestation sites were established in bare ground, the vegetation transition area and *Acacia* woodland when baseline scenario A was adopted for calculating Equation (1).

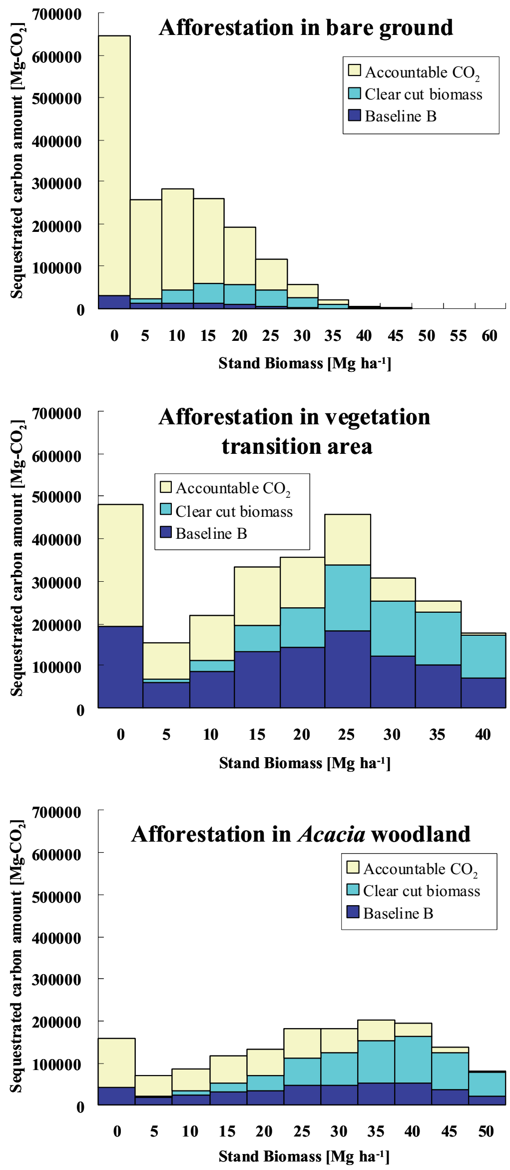

Figure 4. Sequestrated carbon amount by CO_2 conversion when afforestation sites were established in bare ground, the vegetation transition area and *Acacia* woodland when baseline scenario B was adopted for calculating Equation (1).

"Baseline A or B" correspond to $MAI_B \times N \times Area$ and $B \times Area$ of CO_2 conversion in Equation (1), respectively.

Judging from Figure 3, bare ground was considered to be the most suitable afforestation area and its total amount of accountable CO_2 was 1,577 Gg-CO_2. The accountable CO_2 amount per unit area also showed a high value, which varied from 0.5 to 29.4 Mg-CO_2 ha^{-1} as shown in Figure 5. From this figure, the upper limit of the afforestation candidate area was the area whose biomass amount was 65 Mg ha^{-1}; however, regarding efficiency, an area with a high biomass value should be excluded from the afforestation candidate. In this case, it would be better to make afforestation sites in areas whose biomass value is less than 30 Mg ha^{-1}. The carbon sequestration efficiency (accountable CO_2 amount per unit area) varied from 17.0 to 29.4 Mg-CO_2 ha^{-1}, high efficiency. In addition, the afforestation applicable area was estimated as 60,170 ha, which was 98.5% area of bare ground, and was 27.7% area of research area excluding salt lake.

The second and third suitable areas were revealed to be the vegetation transition area and *Acacia* woodland, respectively. However, since a minus count derived from the baseline value of afforestation sites in the vegetation transition area was quite large (about 770 Gg-CO_2 ha^{-1}), the carbon sequestration efficiency of afforestation sites in *Acacia* woodland was greater than that in the vegetation transition area, as shown in Figure 5. For example, the carbon sequestration efficiency of afforestation sites in *Acacia* woodland was 26.0 Mg-CO_2 ha^{-1}, where the original biomass class was from over 5 to less than or equal 10 Mg ha^{-1}, but that of the vegetation transition area was 18.8 Mg-CO_2 ha^{-1} of the same original biomass class. The afforestation applicable area of afforestation sites in the vegetation transition area was 84648 ha, which was 84.0% of the vegetation transition area and 39.0% of the research area. That in *Acacia* woodland was 48660 ha, which was 89.1% of the area of *Acacia* woodland and 22.4% of the research area, excluding salt lake.

Judging from Figure 4 regarding afforestation efficiency, afforestation sites should be established in areas whose original

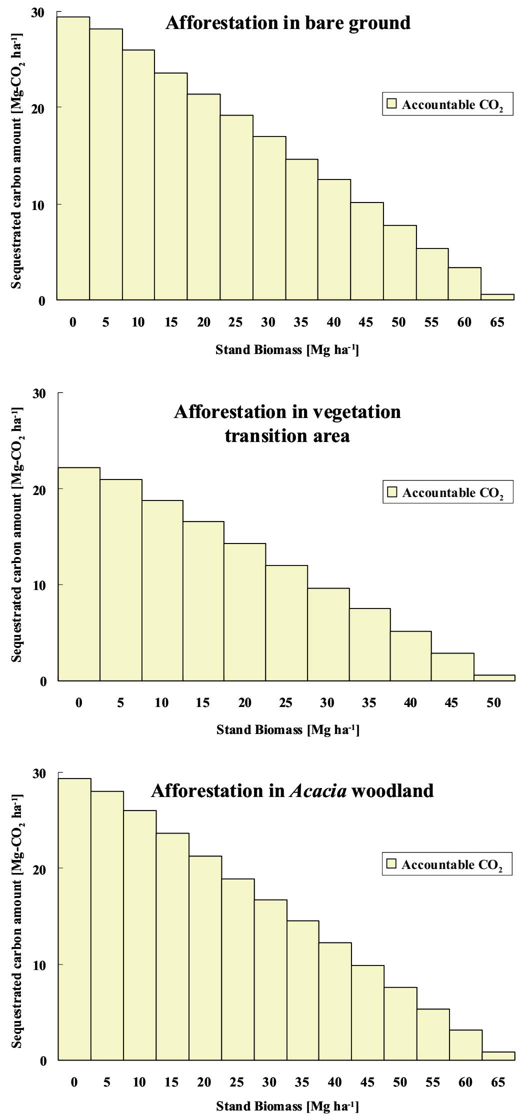

Figure 5. Sequestrated carbon amount per unit area by CO_2 conversion (carbon sequestration efficiency) when afforestation sites were established in bare ground, vegetation transition area and *Acacia* woodland when baseline scenario A was adopted for calculating equation (1).

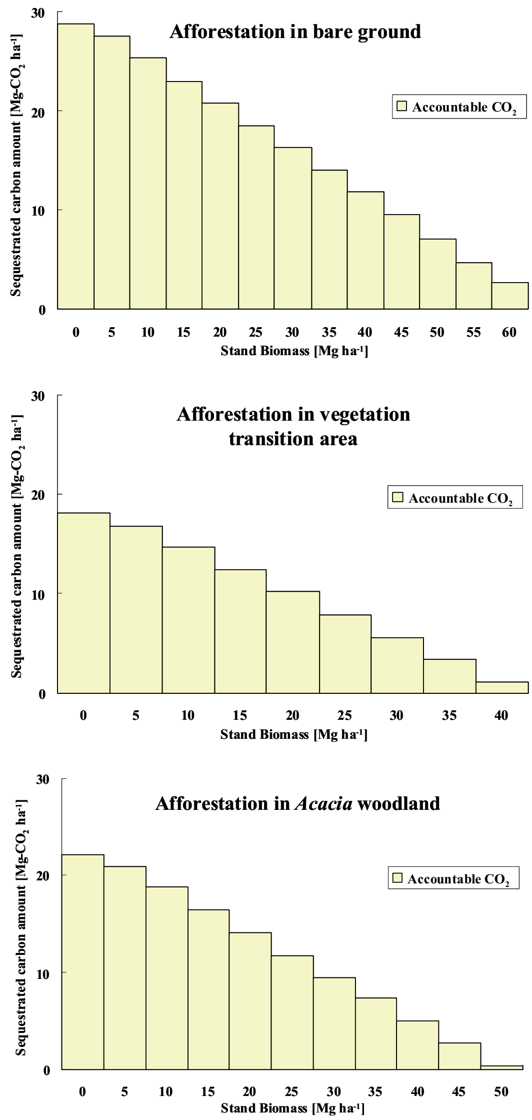

Figure 6. Sequestrated carbon amount per unit area by CO_2 conversion (carbon sequestration efficiency) when afforestation sites were established in bare ground, vegetation transition area and *Acacia* woodland when baseline scenario B was adopted for calculating equation (1).

biomass was less than 30, 30, and 35 Mg ha^{-1} in bare ground, the vegetation transition area, and *Acacia* woodland, respectively. The carbon sequestration efficiency of afforestation sites in bare ground, the vegetation transition area, and *Acacia* woodland varied from 16.3 to 28.7, 5.5 to 18.1, and 7.3 to 22.2 Mg-CO_2 ha^{-1}, respectively, as shown in Figure 6. The afforestation applicable area of afforestation sites in bare ground, the vegetation transition area, and *Acacia* woodland were 60,170, 76,264, and 37,630 ha, which were 98.5%, 75.7%, and 68.9% of the area of each vegetation type and 27.7%, 35.2%, and 17.3% of the research area, excluding salt lake, respectively.

Comparing Figure 4 and Figure 3, since the minus count derived from the baseline value changed as shown in Table 3, the accountable CO_2 amount decreased to a certain extent. Especially, the baseline B value is ten times larger than that of baseline A in *Acacia* woodland; the accountable CO_2 amount was obviously decreased, and the afforestation applicable area was also decreased. As the accountable CO_2 amount varied depending on the baseline scenarios, the baseline estimation method requires high reliability, and the estimated baseline scenario should be carefully checked. In this study, only average data of biomass change in each vegetation type as baseline scenarios were adopted, but, since the baseline data had a certain range, as shown in Table 3, baseline data should be drawn from many cases for a detailed estimation of the accountable CO_2 amount before consulting the UNFCCC.

From the estimation result using Equation (1), as shown in Figures 3 and 4, the accountable CO_2 amount in this research area was calculated. In total, carbon amounts from 1,522 to 1,564, from 910 to 1,287, and from 523 to 919 Gg-CO_2 were accountable for afforestation in bare ground, the vegetation transition area, in *Acacia* woodland in 30 years, respectively. In addition, from 174,000 to 193,000 ha, i.e., from 80.2% to 89.1% of the research area, excluding salt lake, was considered to be an afforestation candidate. Thus, large amounts of carbon will be sequestrated in this arid area, and large amounts of carbon will be accountable as carbon credit.

Since our afforestation method contains a water-harvesting system, only 25% of the afforestation candidate area will be changed to an afforestation site. Conversely, 75% of the afforestation candidate remains original vegetation even when fully used as an afforestation candidate area. Thus, the influence on the natural environment will be kept to a minimum, since species diversity will be conserved in the remaining area. However, the above-mentioned estimation neglected CO_2 emission derived from establishing afforestation sites. On averaging 2.1 Mg-CO_2 ha^{-1} (Tahara *et al*., 2009) will be the cost of making afforestation site. Thus, a total amount from 365 to 405 Gg-CO_2 carbon should be deducted from the carbon credit. This minus value corresponds to about 10% of the accountable CO_2 amount. However, the methods of afforestation establishment are now under improvement, and the CO_2 emission will partially decrease in the near future.

4. CONCLUSIONS

From ground truth and remotely sensed data, the sequestrated carbon amount by planted trees and that by original vegetation as baseline data in each vegetation type and biomass distribution before afforestation were properly examined. Using Equation (1), the accountable CO_2 amount by afforestation in the research area was estimated to be from 2955 to 3770 Gg-CO_2. Thus, even in an arid area, a large amount of CO_2 will be sequestrated in 30 years. In addition, only 25% of the afforestation candidate area will be used as an afforestation site, and 75% will maintain its original vegetation.

Since the accountable carbon credit varied depending on the baseline data, the method and accuracy for estimating baseline data were important, and more detailed research will be necessary in the future.

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ACKNOWLEDGEMENTS

This work was conducted under the support of the Mitsui & Co., Ltd. Environment Fund, the Global Environment Research Fund of The Ministry of Environment of Japan (GHG-SSCP project), and the Core Research for Evolution Science and Technology fund of Science and Technology Agency of Japan.