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Selection of Appropriate Planting Methods and Tree Species for Arid Land Afforestation in Western Australia

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Abstract: As one of the countermeasures against global warming, afforestation in arid land had been proposed and has been tested from 1999. Four types of planting methods and 10 tree species were applied in afforestation test site. In this study, we report analyzed results of which types of planting methods and tree species were appropriate for afforestation in arid land of Western Australia, by comparing biomass growth and survival ratio of planted trees. Multiple comparison analyses were adopted as above described comparison. From our results, *Eucalyptus camaldulensis* was considered as the most suitable tree species for this arid land afforestation, and water-harvesting combined with hardpan blasting was revealed statistically effective to accelerate tree growth and to keep high survival ratio of planted *E. camaldulensis*. Even biomass growth of afforestation site was less than 5 Mg ha^{-1} y^{-1}, this value was much higher than biomass growth of natural vegetation.

Key Words: Bio-energy resource, Carbon mitigation, Hardpan, Statistical analysis.

1. Introduction

Many kinds of countermeasures against global warming have been proposed and tested all over the world, and these countermeasures are categorized as two groups. One is emission reduction such as technology developments on energy saving and renewable energy productions. The other is green house gas (GHG) sequestration such as carbon capture and storage (CCS), and afforestation. By focusing on biomass utilization, Canadel and Raupach (2008) proposed that two approaches to reduce the net increase in atmospheric carbon dioxide concentrations are to replace fossil fuels with renewable biomass or sequester carbon in trees. As one of the carbon sequestration methods using trees, our research team had proposed large scale afforestation methods in arid land, and has been tested afforestation experiments in Leonora, Western Australia (Yamada *et al*., 1999, 2003; Kojima and Egashira, 2011).

In arid land, harsh environmental condition constrains plant growth and survival, and then biomass productivity is usually quite low, however, there are some significant advantages, e.g. almost no land use competition with agriculture in arid land, and tremendously large distribution area. Thus, if some applications overcome such disadvantages of arid land environment and improve growth rate and survival ratio of planted trees, arid land afforestation should acquire huge amounts of CO_2 sequestration potential with the advantage of scale in arid area. Though there are many reports on carbon mitigation in arid area (Glenn *et al*., 1993; Lal, 2001; Burrows *et al*., 2002; Yamada *et al*., 2003; Harper *et al*., 2007; CSIRO, 2009), Australia do not have sufficient data (little empirical data) to inform policy makers in this area (Witt *et al*., 2011). Thus, our reports based on long term afforestation should be considered as greatly contributing to policy making about arid area of Western Australia, and then one of our experimental results is reported in this article.

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. The annual rainfall was calculated as 211 mm (Yasuda *et al*., 2001), and potential evapo-transpiration was observed as 3400 mm y^{-1} (Yamada *et al*., 1999). Actual rainfall from 2000 to 2012 was averaging 258 mm y^{-1} and ranging from 141 to 440 mm y^{-1}. This research area belongs to the Murchison region of Interim Biogeographic Regionalization of Australia (IBRA) Version 5.1 (Environment Australia, 2000). 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

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greenstone strata (Environment Australia, 2000). The dominant land use of this Murchison area is grazing of cattle and/or sheep, and there are some sparsely distributed mine sites of such as iron, nickel and gold. The average grazing pressure in this area was reported as 0.7 AE km^{-2} for cattle and 6.0 DSE km^{-2} for sheep. AE and DSE denote Animal Equivalent (400 kg per head) and Dry Sheep Equivalent (40 kg per head), respectively (Fisher *et al*., 2004).

From the land cover classification result (Suganuma *et al*., 2006a), this research area is classified as 5 types of land cover, i.e. *Acacia* forest and woodland, *Eucalyptus* forest and woodland, bare ground, halophyte and hydrosol (salt lake). In addition, the vegetation of the research area was described as a mixture of *Acacia* open forests, *Acacia* open woodlands and *Acacia* shrublands in the latest vegetation map; further information is available on the National Land and Water Resources Audit (2002).

2.2. Afforestation site

Among several types of afforestation sites established by Yamada *et al*. (2003), the largest afforestation site named “Site C” was chosen for this research. The coordinate of this afforestation site is 121˚0'50"E, 28˚35'20"S, and this can be watched by Google Earth. Ten tree species were selected from native tree species in arid area of Australia as follows, *Acacia aneura*, *A. tetragonophylla*, *Casuarina obesa*, *Eucalyptus camaldulensis*, *E. campaspe*, *E. griffihsii*, *E. lesoueffei*, *E. salburis*, *E. stricklandii* and *E. torquata*. But not all the trees were planted in each afforestation sub-plot.

Four types of afforestation methods were tested in this afforestation site as described on **Figure 1**. Afforestation method 1 adopted water harvesting technique which gathers surface runoff water by large rectangular mound. Afforestation method 2 adopted the same water harvesting technique as method 1, and also adopted hardpan blasting technique invented by Yamada *et al*. (2003). Afforestation method 3 adopted the same hardpan blasting technique as method 2, and also adopted micro-catchment technique which consist of small water harvesting mound around each planted tree. Afforestation method 4 adopted the same micro-catchment and hardpan blasting techniques as method 3, and also adopted additional hardpan blasting technique which assumed to introduce more surface runoff water penetrating into underground, and then supplying planted trees with more available water.

The hardpan was typically distributed under arid and semi-arid condition in Australia, and the hardpan distributing around the research area is called Wiluna Hardpan, which is very hard soil layer developed by progressive silica cementation of deposits (Teakle, 1950: Bettenary and

Table 1. Basic information of afforestation site.

Afforestation methods		Afforestation area [ha]	Tree number [trees]	Tree density [trees ha^{-1}]
Method 1	Water harvesting	0.249	42	169.0
Method 2	Water harvesting + hardpan blasting	0.259	42	162.3
		0.261	42	161.1
		0.219	39	177.8
		0.245	42	171.3
		0.228	42	183.9
		0.240	42	174.8
		0.215	41	190.7
		0.211	42	199.3
		0.249	42	168.4
		0.264	48	181.7
		0.254	48	189.0
Method 3	Micro catchment + hardpan blasting	0.105	18	171.9
Method 4	Micro catchment + double hardpan	0.134	18	134.0

Average tree density is 177.7 trees ha^{-1} (about 7.5 m spacing)

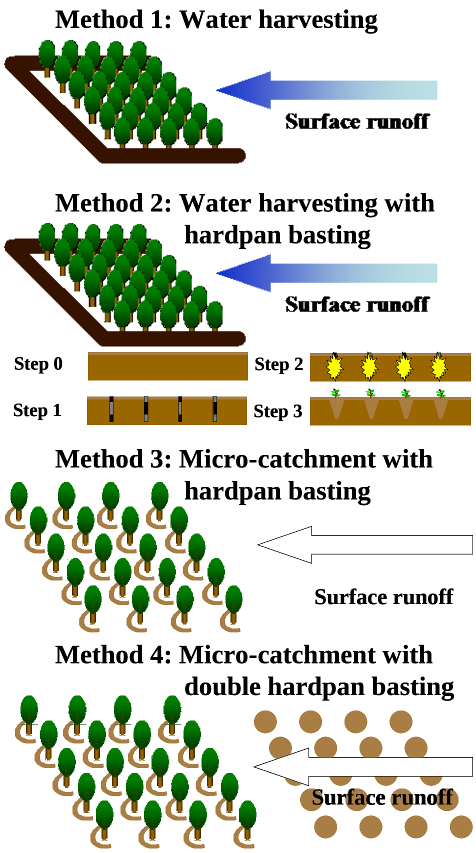

Fig. 1. Conceptual images of each afforestation method. For method 2, step 0 indicates natural regolith condition with thick hardpan layer (over 7 m). Step 1 indicates drilling the holes and filling explosives. Step 2 indicates blasting hardpan layer and making holes. Step 3 indicates filling holes and planting trees.

Churchward, 1974). Hardpan was reported as root impending layer which restricts the rooting depth of plants (Hingston *et al*., 1998). Pracilio *et al*. (2006) also reported that the hardpan constrained the growth of planted trees. Thus, methods 2, 3 and 4 were developed to overcome disadvantages derived from hardpan layer.

Afforestation site was established on August 1999. All trees were planted with 7 m spacing, but actual tree density varied because of the size of water harvesting mounds of each sub-plot. The average tree density is 177 trees ha^{-1}. The average sub-plot size of methods 1 and 2 was 0.24 ha, and that of methods 3 and 4 was 0.12 ha. The basic information of afforestation site is summarized on **Table 1**. To promote taking root of planted trees and to avoid tree death by drought, averaging 8 mm $month^{-1}$ irrigation water was supplied to each planted tree until March 2005 (Shiono *et al*., 2007). After March 2005, the trees grew under completely rain fed condition.

2.3. Statistical analysis

From tree census data from June 2000 to September 2012 and allometric equations made by Shiono *et al*. (2006) and Suganuma *et al*. (2006b), biomass (above and below ground biomass) and survival ratio of each tree species of each sub-plot were calculated. From these calculations, replanted trees were excluded. In addition, the allometric equations of *E. camaldulensis* were applied to other *Eucalyptus* tree species since there was no allometric equation for them.

Obtained data of biomass and survival ratio of each tree species were grouped to each afforestation method, and then summarized on scatter plots. From these scatter plots, candidate data of appropriate combination of tree species and afforestation methods were chosen by rough criterion and statistical analyses. The rough criterion were that survival ratio was over 50% and over 3 tree individuals were survived, because the tree species less than 50% survival ratio were obviously inappropriate for arid land afforestation and small sample number introduced large error and then the reliability of statistical analysis should be greatly declined.

The selected candidate data were tested by statistical analyses which were multiple comparison of difference of population mean (Bonferroni, α=0.05) for biomass data, and multiple comparison of difference of population rate (Bonferroni, α=0.05) for survival ratio data using Excel Statistics (Esumi Co. Ltd.). In the case of prerequisite of statistical analysis was denied, Steel-Dwass test which is nonparametric test was adopted, alternatively. From these statistical analyses, appropriate combination of tree species and afforestation methods were selected.

2.4. Estimation of potential carbon sequestration amount

According to UNFCCC (2006) guideline of Clean Development Mechanism (CDM) afforestation, potential carbon sequestration amount by selected afforestation method and tree species was calculated. Since Australia is categorized the country of Annex I parties of Kyoto Protocol, afforestation activity inside Australia should be carried out under Joint Implementation (JI) afforestation, originally, but there was no guideline of JI afforestation and JI afforestation was considered to be conducted under similar condition with CDM afforestation, thus the guideline by UNFCCC (2006) was used in this study.

According to UNFCCC (2006), carbon sequestered by planted trees was categorized as "actucal net GHG removals by sinks" in two carbon pools (above and blow ground biomass), and was calculated as short term afforestation (20 years) or long term afforestation (30 years). In this study, long term was adopted and calculated as follows.

$$MAI \times N \times 0.5 \times 44 \div 12 \quad (1)$$

MAI denotes mean annual increment [Mg ha^{-1} y^{-1}] and were calculated from tree growth and tree density of each sub-plot. N denotes afforestation length and was 30 years. 0.5 is conversion factor of biomass to carbon, which is used generally (e.g., Ragland *et al*., 1991). 44 and 12 were molecular mass of CO_2 and atomic mass of carbon, respectively.

MAI of each tree species could not be calculated actually because there was no afforestation sub-plot consists of single tree species. Thus, pseudo biomass was introduces to this study, and was calculated as follows.

$$PB = B \times D \times S \quad (2)$$

PB, B, D and S denote pseudo biomass, average biomass of a certain tree species, tree density and survival ratio of a certain tree species, respectively. This pseudo biomass (PB) was used for calculation of mean annual increment (MAI) in this study.

3. Results and Discussion

Annual change of biomass and survival ratio of each planted tree species in afforestation sub-pot made by afforestation method 1 is shown as a scatter plots on **Figure 2**, whose Y-axis is survival ratio [%] and X-axis is average biomass [kg $tree^{-1}$]. From Figure 2, the survival ratio of *E. camaldulensis* once dropped around 70%, but recovered from next year. This indicates that some trees of *E. camalduensis* died apparently after stopping irrigation, which meant there were no green leaves on those trees at the tree census held in 2006, but they have green leaves at the tree census held after 2007. Thus, apparently died trees of *E. camaldulensis* were considered to regenerate by adapting dry condition. From this figure, the tree species whose survival ratio maintained over 50% were *A. aneura*, *A. tetragonophylla* and *E. camaldulensis*, however, the survived tree number were less than 3 individuals for *A. aneura*, *A. tetragonophylla*, and then they were excluded from statistical analyses.

Figure 3 shows the annual change of biomass and survival ratio of each planted tree species in afforestation sub-pots made by afforestation method 2 as the same type of scatter plots. From this figure, the tree species whose survival ratio

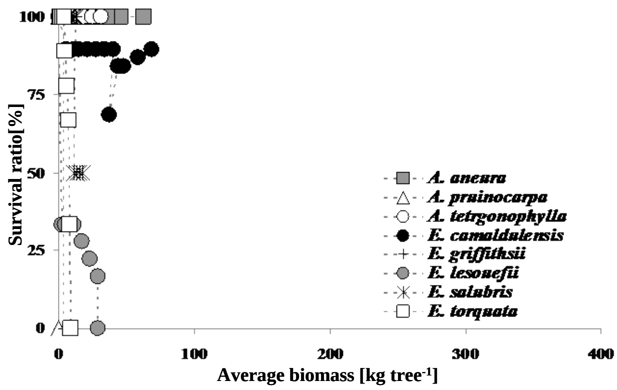

Fig. 2. Average tree biomass and survival ratio of afforestation method 1. Each plot shows calculation results of tree biomass and survival ratio of each tree species of each year (from 2000 to 2012).

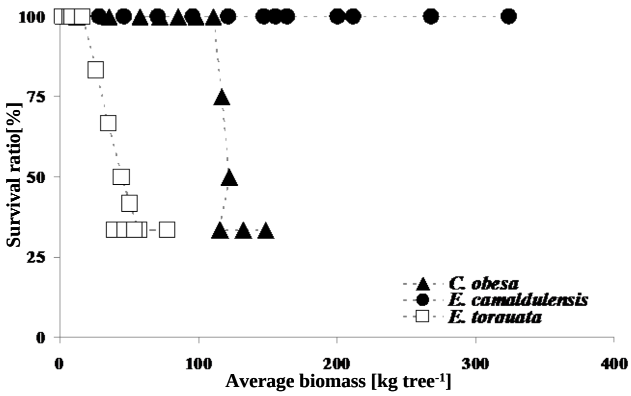

Fig. 4. Average tree biomass and survival ratio of afforestation method 3. Each plot shows calculation results of tree biomass and survival ratio of each tree species of each year (from 2000 to 2012).

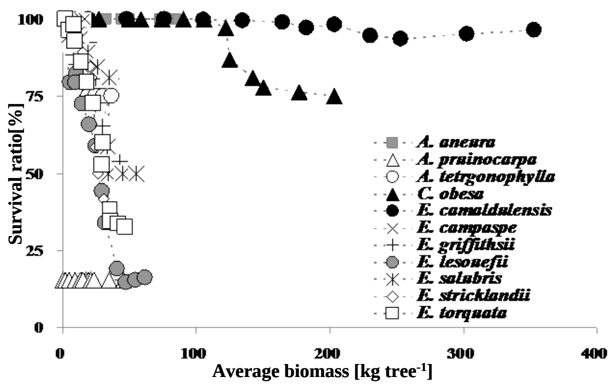

Fig. 3. Average tree biomass and survival ratio of afforestation method 2. Each plot shows calculation results of tree biomass and survival ratio of each tree species of each year (from 2000 to 2012).

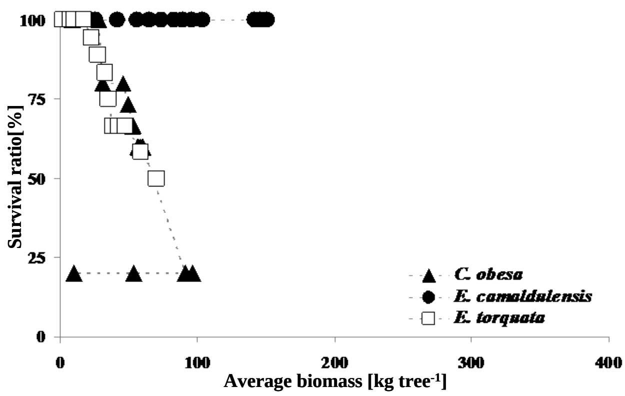

Fig. 5. Average tree biomass and survival ratio of afforestation method 4. Each plot shows calculation results of tree biomass and survival ratio of each tree species of each year (from 2000 to 2012).

maintained over 50% were *A. aneura*, *C. obesa* and *E. camaldulensis*, and then their data were used for statistical analyses.

Figures 4 and **5** show the annual change of biomass and survival ratio of each planted tree species in afforestation sub-pots made by methods 3 and 4 as the same type of scatter plots, respectively. The tree species whose survival ratio maintained over 50% was only *E. camaldulensis* in both figures, and then their data were used for statistical analyses.

By using data samples of selected tree species from Figures 2 to 5, statistical analyses which were multiple comparison of difference of population mean (Bonferroni, α=0.05) for biomass data, and multiple comparison of difference of population rate (Bonferroni, α=0.05) for survival ratio were carried out and their results were summarized on **Table 2**. From these results, the average biomass of *E. camaldulensis*, *C. obesa* and *A. aneura* of afforestation method 2 were significantly the largest, 2nd largest, the smallest among the selected data, respectively. And for other sample data, probably because of sample number shortage (from 5 to 8 trees) and large values of standard deviation (around 100 kg tree^{-1}), obvious significant difference and/or similarity were not

Table 2. Selected combinations of tree species and survival ratio by rough criterion.

Afforestation methods and planted tree species	Average biomass [kg tree^{-1}]	Survival ratio [%]
Method 1: *E. camaldulensis*	68.8 ab	89.5 ab
Method 2: *A. aneura*	72.7 a	100 c
Method 2: *C. obesa*	203.5 b	75.0 a
Method 2: *E. camaldulensis*	352.6 c	96.4 bc
Method 3: *E. camaldulensis*	324.5 bc	100 c
Method 4: *E. camaldulensis*	150.9 ab	100 c

observed, and then ranked as interim like ab or bc. Significantly the highest survival ratio were judged as *A. aneura* of afforestation method 2 and *E. camaldulensis* of afforestation methods 3 and 4. The survival ratio of *C. obesa* of afforestation method 2 was significantly the lowest. And for other sample data were not significantly different and/or similar.

Because of the sufficient sample number (from 29 to 71 trees), the significant differences of average tree biomass among three tree species planted by afforestation method 2 were observed. The biomass of *E. camaldulensis* was about 4 times and 2 times larger than those of *A. aneura* and *C. obesa*, respectively. From the standpoint of average biomass value, *C. obesa* was also considered as appropriate tree species, however, significantly the lowest survival ratio depressed its biomass productivity, which was calculated from pseudo biomass by equation (2). In addition, the decline of the survival ratio of *C. obesa* occured soon after stopping irrigation, and has been continued. Thus, *C. obesa* was judged as not suitable tree species for arid land afforestation.

By comparing afforestation methods using the data of *E. camaldulensis*, the average tree biomass of method 2 was 5 times larger than that of method 1, and their difference was statistically significant, thus hardpan blasting method was considered as effective method for accelerating tree growth in arid area, where hardpan layer constrains plant growth. But hardpan blasting cost too much, and CO_2 emission of afforestation site establishment was also higher than other ordinal afforestation methods, thus whether adopting hardpan blasting method, or not, should be judged as another aspect, e.g. life cycle assessment, in future study.

The average tree biomass and survival ratio of methods 2 and 3 were not significantly different. Thus, both water harvesting techniques by large rectangular mound and micro catchment combined with hardpan blasting were considered as effective methods for arid land afforestation. Thus, which types of water harvesting techniques were adopted should be judged by another aspect (e.g. cost effectiveness).

Afforestation method 4 obviously had disadvantage of cost and biomass productivity compared to afforestation methods 2 and 3, thus this method should be excluded from candidates of afforestation methods in arid land.

By using the data of *E. camaldulensis* planted by afforestation method 2, which had the largest sample number, and equations (1) and (2), MAI and potential carbon sequestration amount were calculated as 4.41 Mg ha^{-1} y^{-1} and 243 Mg-CO_2e ha^{-1}, respectively. For MAI of original vegetation, which is *Acacia* woodland and open forest dominated by *A. aneura*, was observed as about 0.2 Mg-CO_2e ha^{-1} y^{-1} (Suganuma *et al.*, 2012), and that of similar vegetation in Queensland, which was Mulga open forest also dominated by *A. aneura*, was reported as from 0.73 to 0.91 Mg-CO_2e ha^{-1} y^{-1} (Witt *et al*., 2011). Considering these data, *E. camaldulensis* planted by afforestation method 2 was quite effective for carbon mitigation in arid area of Western Australia. In addition, since *E. camaldulensis* is native tree species and also observed inside research area, and afforestation area consists of plantation area (25%) and conservation area as it is for water harvesting (75%), the impact to the natural environment by applying this type of afforestation techniques should be reduced to the minimum.

On the other hand, comparing the growth rate of general plantation and/or afforestation using *Eucalyptus* species in temperate and tropical area reported as over 25 Mg ha^{-1} y^{-1} (Tzanakakis *et al*., 2009) and 45-60 m^3 ha^{-1} y^{-1} (FAO, 2005), 4.41 Mg ha^{-1} y^{-1} is quite slow tree growth. From the report of Hassel and Associates (1996), the tree growth rate of 4.41 Mg ha^{-1} y^{-1} is categorized as the lowest productivity of the *Eucalyptus* forest. So this biomass growth rate is not so high in general. But comparing the carbon sequestration rate which was from 1.4 to 2.6 Mg-CO_2e ha^{-1} y^{-1} of *Eucalyptus* woodlands in Queensland (annual rainfall: 200-800 mm) reported by Burrows *et al.* (2002), about 8 Mg-CO_2e ha^{-1} y^{-1} carbon sequestration rate (equivalent to 4.41 Mg ha^{-1} y^{-1} biomass growth rate) in our study area (annual rainfall: around 200 mm) was considered as relatively high in arid land. In addition, since there are about 650,000 km^2 area of the same vegetation and the same land use as research area in Western Australia (National Land and Water Resources Audit, 2002), this arid land afforestation was considered to receive the advantage of scale, and to have possibility of huge CO_2 sequestration.

4. Conclusion

From afforestation experiments in Sturt Meadows in arid area of Western Australia and statistical analyses, the *E. camaldulensis* (native tree species) monoculture afforestation with water harvesting combined with hardpan blasting techniques was considered as the most appropriate afforestation method for this arid area from the viewpoint of biomass productivity (i.e. carbon sequestration amount), and to have the potential to sequester huge amounts of CO_2 by making the most use of advantage of scale in future practice.

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