RELEASE CHARACTERISTICS AND EFFECTS ON EUCALYPTUS TREE GROWTH OF FERTILIZER FROM WOOD RESIDUE SLOW-RELEASE FERTILIZER SHELL

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(Received December 2015)

Abstract. To investigate the release characteristics and effects on tree growth of fertilizer from wood residue slow-release fertilizer shells, fertilizer was loaded into the wood residue shells and the resultant slow-release fertilizers were evaluated using eucalyptus fertilization tests. The growth parameters (girth, height, and standing volume) and nutrient contents of soil and tree leaves were monitored regularly to evaluate the effects of wood residue slow-release fertilizer shells on tree growth and to determine the process by which fertilizer was released. Fertilizer-loaded *Pinus massoniana* and *Toona sinensis* shells and straight fertilizer can all significantly improve growth, eg girth at breast height, height, and standing volume. The K, N, and P contents in soil and tree leaves were not significantly different among groups treated with *P. massoniana* and *T. sinensis* residue shell slow-release fertilizer and straight fertilizer, which suggests that these three fertilizers did not differ with respect to effects on soil nutrients and leaf nutrients. Wood residue shell slow-release fertilizer can significantly increase tree growth, including growth in girth, height, and standing volume. These shells provide satisfactory fertilizer release dynamics. *Toona sinensis* shells provided better slow-release properties than did *P. massoniana* shells.

Keywords: Forest fertilization test, nutrients, tree growth, wood residue shell slow-release fertilizer.

INTRODUCTION

Controlled/slow-release fertilizers (CRF) have many advantages compared with traditional fertilizers, such as greater efficiency, minimal environmental pollution, longer duration, and decreased labor costs. As a result, CRF technology has become a focus of the modern agricultural industry. Since slow-release urea formaldehyde was patented in Europe in 1924; CRF technology has developed rapidly and has become more and more widely used in production agriculture (Han and Gong 2005). Development and production of CRF first started in the United States in the 1960s. Japan, Canada, Britain, Israel, and France soon followed (Zaidel 1996; Shaviv 2000; Jarosiewica and Tomaszewska 2003). CRF technology, which involves creating coatings using

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Wood and Fiber Science, 48(4), 2016, pp. 217-227

different techniques and various materials, has been studied by many researchers. The coating materials include but are not limited to sulfur (Grigori et al 1990; Wu and Chen 2003), polyolefins (Ni 2012), thermosetting resin polymer (Lu and Zhou 1994), natural polymer products (Tangboriboonrat and Sirichaiwat 1996), modified natural rubber (Seng and Fong 1985), and polysulfone and starch (Anna and Maria 2002; Maria et al 2002; Tomaszewska and Jarosiewicz 2004). Long-lasting ammonium bicarbonate coated with fused calcium magnesium phosphate was one of the first CRF to be used in China (Zhu et al 2008). Since the 1970s, CRF-related research, especially the preparation of granules of water-soluble fertilizers with insoluble coatings, has developed rapidly. Most of the studies have focused on the selection of coating materials, investigation of controlled-release mechanisms, and the evaluation of effectiveness of CRF. (Feng et al 2010). Zhang et al (2005) reported the preparation of urea coated with controlled-release organic and inorganic materials. Liu et al (2006) prepared natural kaolin-based cementing and coating material. This material absorbed fertilizer nutrients N, P, K, and organic carbon satisfactorily and had a high viscosity. Shi et al (2006) prepared CRF using tung oil as a coating material. Qin et al (2008a, 2008b) used water-based polyurethane and aqueous acrylic solutions as coating material to prepare new CRF.

Although coated fertilizers have satisfactory controlled- and slow-release effects, they have some limitations. For example, the preparation of organic coated fertilizer is relatively complicated. The coating materials are not biodegradable, which causes environmental pollution. To decrease pressure on the environment, biodegradable materials are highly desirable. Wood is porous, permeable, and readily degradable. With the use of fertilizer shells made from wood residues and adhesives, the fertilizer will, under the action of rain, dissolve in water, first seeping through the wood's inherent internal voids and channels, then seeping through additional voids and channels caused by adhesive degradation, providing nutrients to plants. The release of fertilizer can provide a steady and long-lasting stream of exudation, which not only ensures a continuous nutrient supply but also prevents the harm that can be caused by one-time overfertilization. Wood residues are abundant natural resources, and the adhesives can be biodegradable natural polymer materials. Using wood residue and natural adhesives as raw materials for slow-release fertilizer shells has the least impact on the environment possible for the effect desired.

Wood residue shell slow-release fertilizer is a new means of preparing controlled- or slow-release fertilizer. Fu et al (2007, 2010, 2014a, 2014b) successfully prepared wood residue shell slow-release fertilizer, published repeatedly, and now hold three related patents. However, the dynamics of the release of fertilizer and the effects of wood residue shell slow-release fertilizer on plant growth have not been fully characterized. In this study, a forest fertilization test was performed to investigate the mechanisms associated with wood residue shell slow-release fertilizer and its effects on plant growth. Increases in plant growth and nutrient contents in soil and tree leaves were monitored. The results of this study will provide a solid foundation for preparation and application of wood residue shell slow-release fertilizer.

MATERIALS AND METHODS

Wood Residues and Adhesive

Wood residues of two species, *Pinus massoniana* and *Toona sinensis*, were purchased from a local sawmill. The initial MC of the wood residues, about 10%, was maintained. The wood residues were sieved to average particle size of 0.64-1.4 mm for shell preparation. Commercially available adhesive was used in this study; it had a solids content of 53% and curing temperature of 105-125°C.

Instruments

The major instruments used in this study included a wood-based panel press machine XLB100-D (Huzhou Xingli Rubber Machinery Manufacturing

Company, Huzhou, China), altimeter XRC-110 (Xuzhou Huangshan Instrument Factory, Xuzhou, China), flame photometer 6400A (Shanghai precision Scientific Instruments Company, Shanghai, China), and UV spectrometer GE Ultrospec 2100 (General Electric Company-China Branch, Guangzhou, China).

Manufacturing of Wood Residue Shell

Pinus massoniana and *Toona sinensis* wood residues served as raw materials to manufacture wood residue slow-release fertilizer shells. Secondary molding methods were also used. The wood residues were mixed with adhesive at a 6:1 ratio and were then used for pressing plates. The density of the plate was 550 kg/m^3. The thickness of the plate was 8 mm. The pressed plate was cut into 60- × 60-mm pieces, which were then glued together using hot melt adhesive into cube-shaped shells (Fig 1).

Forest Fertilization Test

The effects of wood residue shell slow-release fertilizer made from wood residues of *P. massoniana* and *T. sinensis* on the growth of eucalyptus (*Eucalyptus urophylla* clones DH32-28) were tested in a field experiment performed at the Lianshan Station, Liang Feng Jiang Forest Farm, Nanning, Guangxi Province, China, on August 21, 2013. The experimental site (lat. N 22°36′08.13″, long. E 108°18′15.60″) located in the middle of a south-facing slope at an elevation of 250 m. The experimental procedures are subsequently described:

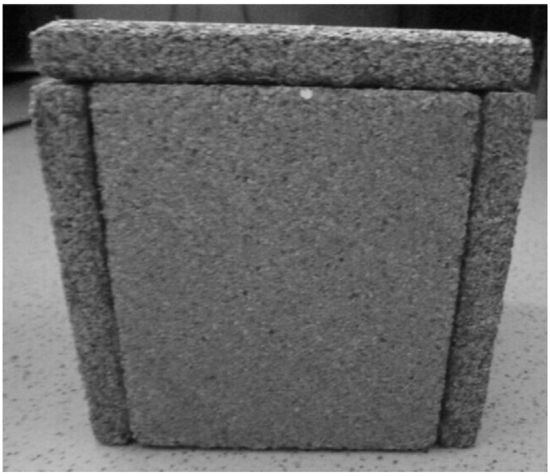

Figure 1. Slow-release fertilizer shell made from *Toona sinensis* residue.

1. Site: The experimental site consisted of three blocks. Each block consisted of three parallel sets of plots. Each plot was 20 × 20 m and received the same treatment. Neighboring plots were separated by two eucalyptus trees. In each plot, there were 67 eucalyptus trees, and the trees were 2 × 3 m away from each other.
2. Fertilization: About 250 g of Stanley fertilizer (Stanley Fertilizer Co., Ltd., Guigang, China) was loaded into the testing shells. At 0.3 m from both sides of each eucalyptus tree, a 0.2- × 0.2- × 0.2-m hole was dug and the fertilizer was placed in the hole. Then the hole was covered with soil. The same treatment was performed on all the trees in the same block: plots 1, 4, and 7 were treated with *P. massoniana* shells; plots 2, 5, and 8 were treated with *T. sinensis* shells; and plots 3, 6, and 9 were treated with Stanley fertilizer without shells.
3. Measurement of tree growth: The girth at breast height, overall height, and standing volume of each tree were measured 1 da before application of fertilizer and then periodically afterward. The difference between two measures was calculated to indicate tree growth. Measurements of girth and height of each eucalyptus tree were performed on the 23rd of each of the first 10 mo; then the measurements were performed every 3 mo for another 6 mo. A total of 12 measurements were performed. The girth of a tree was measured at 1.3 m above the ground, and the height of the tree was measured using an any-point laser altimeter.

The standing volume of each tree was calculated based on previous literature (Cen 2007):

$$V = C_0 \times D^{C_1 - C_2 \times (D+H)} \times H^{C_3 + C_4 \times (D+H)}$$

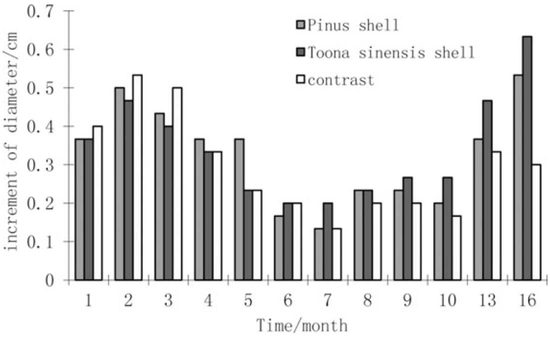

Figure 2. Increase in girth of eucalyptus tree with time.

Here, V is standing volume (m^3), D is girth at breast height, and H is tree height. C_0, C_1, C_2, C_3, and C_4 are constants: $C_0 = 1.09154145 \times 10^{-4}$, $C_1 = 1.87892370$,$C_2 = 5.69185503 \times 10^{-3}$, $C_3 = 0.65259805$, and $C_4 = 7.84753507 \times 10^{-3}$.

4. Sample collection: The soil and leaf samples were collected four times on the 23rd of every other month. Five soil subsamples were collected from 0.2-m-deep holes located at the center of each plot. The subsamples were mixed together to represent the soil of this plot. Similarly, five leaf subsamples (100 g each) were collected from the middle of the latest flush of five trees located at the diagonal center of each plot. The subsamples were mixed together to represent the leaves of the trees in one plot. The leaf samples were air-dried and analyzed for N, K, and P nutrient contents. Collection of leaf samples ceased after month 8 because the eucalyptus trees had then grown too tall for easy leaf collection.

Analysis of Soil Nutrients

After the grinding and sieving process, the soil samples were subjected to N, P, and K analysis. The N, P, and K analyses were performed using the Chinese Forestry Science Academy Standards (1999a, 1999b, 1999c) LY/T 1228-1999, LY/T 1232-1999, and LY/T 1234-1999, respectively.

Analysis of Leaf Nutrients

After grinding and sieving, the leaf samples were subjected to N, P, and K analysis. The N analysis was performed according to The Chinese Forestry Science Academy (1999d, 1999e) LY/T 1269-1999 and LY/T 1271-1999, respectively.

Statistical Analysis

SAS software (Carey, NC) was used for statistical analysis. Analysis of variance was used to assess the performance of different fertilizers. When the F test indicated that a factor was significant, Duncan's multiple range tests were performed to further determine the level of significance of that factor.

RESULTS AND DISCUSSION

Wood Residue Shell Slow-Release Fertilizer and Eucalyptus Tree Growth

Wood residue shell slow-release fertilizer and girth of eucalyptus trees. Before the application of fertilizer, the average girth of the eucalyptus trees in the *P. massoniana* shell group, *T. sinensis* shell group, and straight fertilizer

Table 1. Wood residue shell slow-release fertilizer and girth at breast height of eucalyptus trees.

Treatment	Increase in girth per centimeter					
	1	2	3	4	5	6
Pinus massoniana shells	6.90 ± 0.22a	7.40 ± 0.08a	7.83 ± 0.09a	8.20 ± 0.08a	8.57 ± 0.12a	8.73 ± 0.09a
Toona sinensis shells	7.00 ± 0.31a	7.43 ± 0.26a	7.83 ± 0.12a	8.17 ± 0.12a	8.40 ± 0.29a	8.60 ± 0.22ab
Straight fertilizer	6.63 ± 0.31a	7.17 ± 0.19a	7.67 ± 0.12a	8.00 ± 0.24a	8.23 ± 0.25a	8.43 ± 0.12b
	7	8	9	10	13	16
P. massoniana shells	8.87 ± 0.05a	9.10 ± 0.08a	9.33 ± 0.05a	9.53 ± 0.12a	9.90 ± 0.08a	10.43 ± 0.05a
T. sinensis shells	8.80 ± 0.14a	9.03 ± 0.12a	9.30 ± 0.08a	9.57 ± 0.12a	10.03 ± 0.12a	10.67 ± 0.12a
Straight fertilizer	8.57 ± 0.05b	8.77 ± 0.09a	8.97 ± 0.05b	9.13 ± 0.05b	9.47 ± 0.05b	9.77 ± 0.05b

a and b represent α levels at 5%.

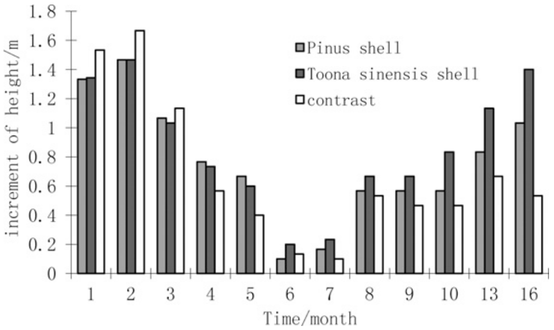

Figure 3. Increase in height of eucalyptus tree with time.

group was found to be 6.53, 6.60, and 6.23 cm, respectively. The girths of eucalyptus trees in each group after fertilizer application and the statistical analysis are shown in Fig 2 and Table 1, respectively.

As shown in Fig 2 and Table 1, the rate of girth growth increased initially and then showed a decreasing trend in all three treatment groups. During the first 3 mo, the increase in girth of eucalyptus trees treated with straight fertilizer was greater than those of trees treated with *P. massoniana* shells or *T. sinensis* shells. Between the 4th and 6th months, the trees in the straight fertilizer and wood shell slow-release fertilizer groups showed roughly the same increases in girth. However, beginning during the 7th month, the increases in girth of eucalyptus trees treated with wood residue shell slow-release fertilizers were greater than those of trees treated with straight fertilizer, and the difference became more significant with time. At the 16th month, the cumulative gain in girth of trees treated with straight fertilizer was only 56.6% that of trees treated with *P. massoniana* shells and 46.9% that of trees treated with *T. sinensis* shells. The use of shells was found to slow down the release of fertilizer but these slow-release fertilizers also maintained relatively high concentrations in the trees' environments for a longer period and therefore prolonged the fast-growth period of eucalyptus trees. Further comparison indicated that between the 2nd and 4th months, the increase in girth of eucalyptus trees treated with *P. massoniana* shells was slightly greater than that of trees treated with *T. sinensis* shells, but the difference was not significant. Between the 7th and 16th months, the increase in girth of eucalyptus trees treated with *P. massoniana* shells was slightly lower than that of trees treated with *T. sinensis*, but this difference was also not significant. These results suggested that *P. massoniana* shells had a higher fertilizer release rate and led to faster initial growth, but *T. sinensis* shells had better slow-release properties and could maintain fast growth for a longer period. During the 16-mo measurements, the gain of girth of eucalyptus trees was 3.9, 4.07, and 3.53 cm for trees treated with *P. massoniana* shells, *T. sinensis* shells, and straight fertilizer, respectively.

Wood residue shell slow-release fertilizer and height of eucalyptus trees. The tree height before the application of fertilizer was 7.67, 7.39, and 7.27 m for *P. massoniana* shells, *T. sinensis* shells, and free fertilizer treated trees, respectively. The increases in tree height and the results of statistical analysis are shown in Fig 3 and Table 2, respectively.

Table 2. Wood residue shell slow-release fertilizer and the height of eucalyptus trees.

	Increase in height per meter					
Treatment	1	2	3	4	5	6
Pinus massoniana shells	8.93 ± 0.21a	10.47 ± 0.29a	11.53 ± 0.12a	12.30 ± 0.08a	12.97 ± 0.12a	13.07 ± 0.12a
Toona sinensis shells	8.80 ± 0.12a	10.47 ± 0.08a	11.23 ± 0.17a	11.97 ± 0.17a	12.57 ± 0.17a	12.77 ± 0.12a
Straight fertilizer	8.73 ± 0.43a	10.20 ± 0.76a	11.60 ± 0.29a	12.17 ± 0.29a	12.57 ± 0.33a	12.70 ± 0.33a
	7	8	9	10	13	16
P. massoniana shells	13.23 ± 0.05a	13.80 ± 0.33a	14.37 ± 0.48a	14.93 ± 0.52a	15.77 ± 0.26ab	16.80 ± 0.33a
T. sinensis shells	13.00 ± 0.08a	13.67 ± 0.41a	14.33 ± 0.39ab	15.17 ± 0.42a	16.30 ± 0.29a	17.70 ± 0.43a
Straight fertilizer	12.80 ± 0.33a	13.33 ± 0.05a	13.80 ± 0.28b	14.27 ± 0.45b	14.93 ± 0.46b	15.47 ± 0.29b

a and b represent α levels at 5%.

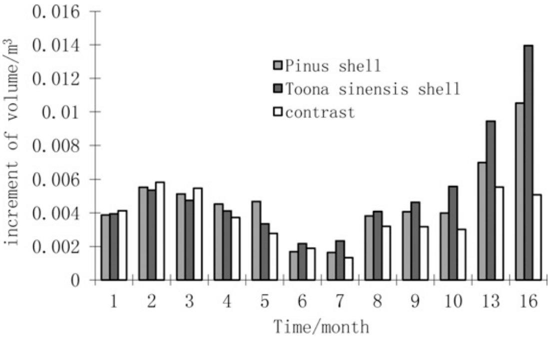

Figure 4. Increase in standing volume of eucalyptus tree with time.

As shown in Fig 3 and Table 2, height gain was different among trees treated with *P. massoniana* shells, *T. sinensis* shells, and free fertilizer. From the 1st to the 3rd mo, trees treated with shells grew more than those treated with straight fertilizer. In the 6th and 7th mo, the increase in height was relatively small for all groups because it was January and February, when temperatures are low and the tree growth slows down. From the 3rd to 5th mo, the increase in height of trees treated with *P. massoniana* shells was slightly greater than that of trees treated with *T. sinensis* shells, although the difference was not statistically significant. From the 8th to 16th mo, the increase in height of trees treated with free fertilizer was less pronounced than that of trees treated with shells. The difference became more noticeable during the 9th month. In addition, the increase in height of trees treated with *T. sinensis* shells was slightly greater than that of trees treated with *P. massoniana* shells, but the difference was not statistically significant. During the 16th month of the experimental period, the increase in height of eucalyptus trees was 9.13 m, 10.31 m, and 8.20 cm in groups treated with *P. massoniana* shells, *T. sinensis* shells, and straight fertilizer, respectively.

Wood residue shell slow-release fertilizer and standing volume of eucalyptus trees. Before the application of fertilizer, the standing volume of eucalyptus trees was 0.0152, 0.015, and 0.0134 m^3 for trees treated with *P. massoniana* shells, *T. sinensis* shells, and free fertilizer, respectively. The change of standing volume and the statistical analysis results are shown in Fig 4 and Table 3, respectively.

Changes in standing volume are an important indicator of tree growth. For trees of the same species and stand age, larger standing volume indicates faster growth (Pan et al 2004). As shown in Fig 4 and Table 3, during the first 3 mo, the standing volume of trees treated with straight fertilizer was greater than that of trees treated with shells, but the difference was not significant. The increase in the standing volume of trees treated with *P. massoniana* shells was more pronounced than that of trees treated with *T. sinensis* shells. During the 16 mo of the experimental period, the standing volume increased by 0.0565, 0.0637, and 0.0452 m^3 among trees treated with *P. massoniana* shells, *T. sinensis* shells, and free fertilizer, respectively.

Wood Residue Shell Slow-Release Fertilizer and Soil Nutrient Parameters of Soil Samples

As shown in Fig 5 and Table 4, the amount of K in the soil samples collected before and after the application of fertilizer was not significantly

Table 3. Wood residue shell slow-release fertilizer and the standing volume of eucalyptus trees.

	Standing volume ($\times 10^{-3}$/tree)					
Treatment	1	2	3	4	5	6
Pinus massoniana shells	19.0 ± 1.5a	24.6 ± 0.6a	29.8 ± 0.4a	34.3 ± 0.8a	39.0 ± 0.7a	40.6 ± 0.6a
Toona sinensis shells	18.9 ± 1.8a	24.3 ± 1.7a	29.1 ± 0.5a	33.2 ± 0.5a	36.5 ± 2.0ab	38.7 ± 1.8ab
Straight fertilizer	17.5 ± 2.1a	23.3 ± 2.5a	28.8 ± 1.5a	32.5 ± 2.5a	35.3 ± 2.8b	37.2 ± 1.9b
	7	8	9	10	13	16
P. massoniana shells	42.3 ± 0.3a	46.1 ± 0.9a	50.2 ± 1.8a	55.3 ± 3.0a	61.1 ± 1.8a	71.7 ± 2.0a
T. sinensis shells	41.0 ± 1.4a	45.1 ± 2.3ab	49.7 ± 2.0a	54.2 ± 2.6a	64.8 ± 2.5a	78.7 ± 3.3a
Straight fertilizer	38.5 ± 1.2b	41.7 ± 1.0b	44.9 ± 1.1b	47.9 ± 1.5b	53.4 ± 2.1b	58.5 ± 1.5b

a and b represent α levels at 5%.

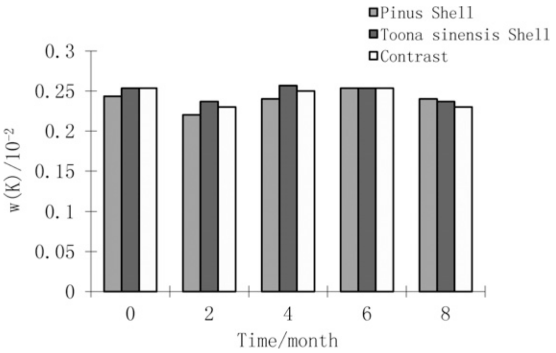

Figure 5. Change in K levels in soil samples.

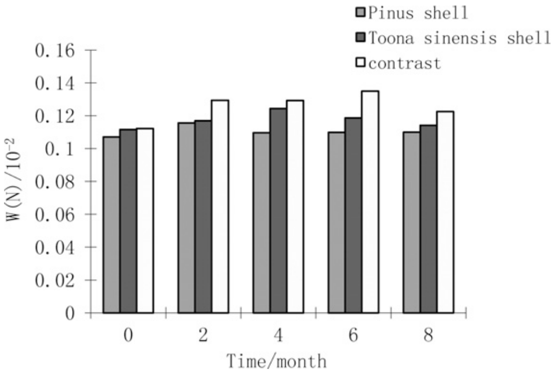

Figure 6. Change in N levels in soil samples.

different. In addition, the amount of K was not significantly different in the soil samples collected from the plots treated with *P. massoniana* shells, *T. sinensis* shells, or straight fertilizer. These results showed that the amount of K in the soil was not affected by type of fertilizer used.

As shown in Fig 6 and Table 5, the amount of N in the soil samples collected before and after application of fertilizer was not significantly different. In addition, the amount of N was not significantly different in the soil samples collected from the plots treated with *P. massoniana* shells, *T. sinensis* shells, or straight fertilizer. These results showed that the amount of N in the soil was not affected by type of fertilizer used.

As shown in Fig 7 and Table 6, the amount of P in the soil samples collected before and 2 mo after application of fertilizer was not significantly different. However, the amount of P was significantly different in the soil samples collected 4 and 6 mo after application of fertilizer. These results suggested that the amount of P in the soil could be affected by type of fertilizer used.

Wood Residue Slow-Release Fertilizer Shells and Nutrients in Leaves of Eucalyptus Trees

Amount of K in leaves of eucalyptus trees. As shown in Fig 8 and Table 7, the amount of K in the leaves collected before and after application of fertilizer was not significantly different. In addition, the amount of K was not significantly different in leaf samples collected from trees treated with *P. massoniana* shells, *T. sinensis* shells, or straight fertilizer. These results indicated that the amount of K in the leaves was not affected by type of fertilizer used.

Amount of N in leaves of eucalyptus trees. As shown in Fig 9 and Table 8, the amount of N in the leaves collected before and right after application of fertilizer was not significantly different. However, starting during the 6th mo after application of fertilizer, the amount of N was significantly different in the leaf samples from the three groups. These results suggested that the amount of N in the leaves was not affected by type of fertilizer used.

Table 4. Wood residue shell slow-release fertilizer and potassium concentration in soil samples.

Treatment	Content in soil ($w[K]/10^{-2}$)				
	0	2	4	6	8
Pinus massoniana shells	0.243 ± 0.040a	0.220 ± 0.030a	0.240 ± 0.030a	0.250 ± 0.030a	0.240 ± 0.050a
Toona sinensis shells	0.253 ± 0.050a	0.240 ± 0.050a	0.260 ± 0.050a	0.250 ± 0.050a	0.240 ± 0.040a
Straight fertilizer	0.253 ± 0.040a	0.230 ± 0.020a	0.250 ± 0.030a	0.250 ± 0.030a	0.230 ± 0.020a

a and b represent α levels at 5%.

Table 5. Wood residue shell slow-release fertilizer and N content in soil samples.

	Content in soil (w[N]/10^{-2})				
Treatment	0	2	4	6	8
Pinus massoniana shells	0.107 ± 0.011a	0.116 ± 0.001a	0.110 ± 0.013a	0.110 ± 0.006a	0.110 ± 0.012a
Toona sinensis shells	0.112 ± 0.003a	0.117 ± 0.002a	0.124 ± 0.004a	0.119 ± 0.010a	0.114 ± 0.010a
Straight fertilizer	0.112 ± 0.012a	0.129 ± 0.018a	0.129 ± 0.015a	0.135 ± 0.020b	0.123 ± 0.020a

a and b represent α levels at 5%.

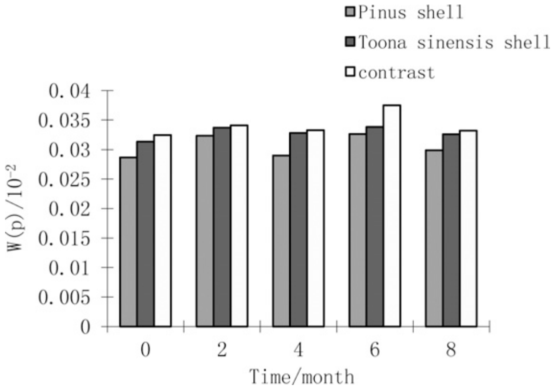

Figure 7. Change in P levels in soil samples.

Table 6. Wood residue shell slow-release fertilizer and P concentration in soil samples.

	Content in soil (w[P]/10^{-2})				
Treatment	0	2	4	6	8
Pinus massoniana shells	0.029 ± 0.002b	0.032 ± 0.005a	0.029 ± 0.004b	0.033 ± 0.005a	0.030 ± 0.003b
Toona sinensis shells	0.031 ± 0.003a	0.034 ± 0.004a	0.033 ± 0.002 a	0.034 ± 0.003a	0.033 ± 0.003a
Straight fertilizer	0.032 ± 0.001a	0.034 ± 0.001a	0.033 ± 0.002a	0.038 ± 0.004a	0.033 ± 0.002a

a and b represent α levels at 5%.

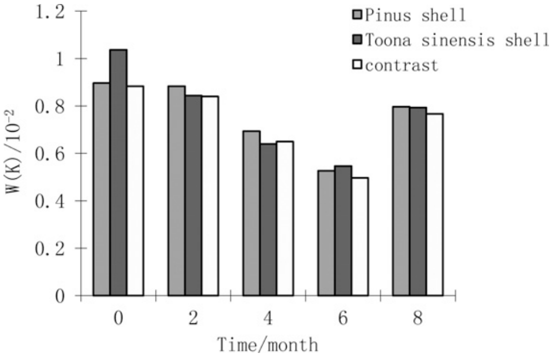

Figure 8. Change in K levels in eucalyptus tree leaves.

Table 7. Wood residue shell slow-release fertilizer and K concentration in eucalyptus tree leaves.

	Content in leaves (w[K]/10^{-2})				
Treatment	0	2	4	6	8
Pinus massoniana shells	0.897 ± 0.052a	0.883 ± 0.025a	0.693 ± 0.026a	0.527 ± 0.025a	0.797 ± 0.074a
Toona sinensis shells	1.037 ± 0.144a	0.843 ± 0.054a	0.640 ± 0.033a	0.547 ± 0.024a	0.793 ± 0.083a
Straight fertilizer	0.883 ± 0.062a	0.840 ± 0.033a	0.650 ± 0.029a	0.497 ± 0.067a	0.767 ± 0.034a

a and b represent α levels at 5%.

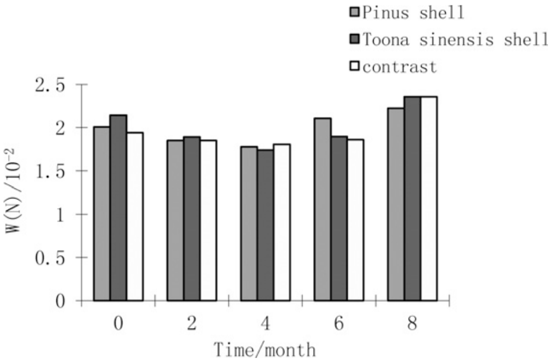

Figure 9. Change in N levels in eucalyptus tree leaves.

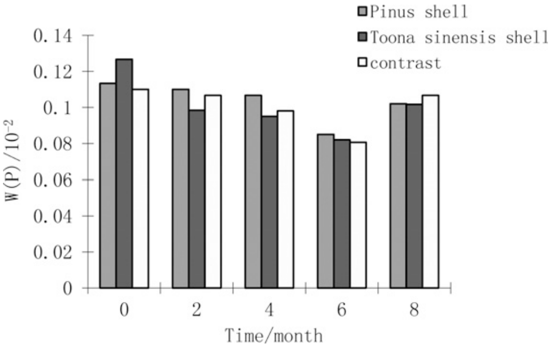

Figure 10. Change in P levels in eucalyptus tree leaves.

Amount of P in leaves of eucalyptus trees. As shown in Fig 10 and Table 9, the amount of P in the leaves collected before and right after application of fertilizer was not significantly different. However, the amount of P was significantly different in the leaf samples collected from trees treated with *P. massoniana* shells and *T. sinensis* shells 2 mo after application. These results showed that the amount of P in the leaves was not affected by type of fertilizer used.

CONCLUSION

In this study, three types of fertilizer were tested for their effects on the growth of eucalyptus trees. The three types were fertilizer-loaded *P. massoniana* and *T. sinensis* shells and straight fertilizer without any carrier. Results indicated that all three methods increased growth significantly, including girth at breast height, overall height, and standing volume. During the first 3 mo after application of fertilizer, the increases in girth, height, and standing volume of trees treated with straight fertilizer were slightly but not significantly greater than those of the trees treated with fertilizer-loaded wood residue slow-release shells. Beginning during the 4th mo after application, all the growth increments (girth, height, and standing volume) of the trees treated with wood residue shell slow-release fertilizer were significantly greater than those treated with straight fertilizer. Average values of girth, height, and standing volume of shell-treated trees were at least 0.37 cm, 0.93 m, and 0.0113 m^3, respectively, greater than those treated with straight fertilizer. Regarding wood residue, shells made from *P. massoniana* and *T. sinensis* residues were not found to be different during the first few months after application with respect to effects on increases in girth, height, and standing volume. However, 6-8 mo after the application of fertilizer, shells made from *T. sinensis* residues were associated with slightly greater increases in growth, although this difference was not significant.

K, N, and P contents in soil and tree leaves were not significantly different among *P. massoniana* shells, *T. sinensis* shells, and straight fertilizer. These results suggested that the three types of fertilizer were not different with respect to their effects on soil nutrients and leaf nutrients.

In summary, wood residue shell slow-release fertilizer can significantly increase tree growth,

Table 8. Wood residue shell slow-release fertilizer and N concentration in eucalyptus tree leaves.

	Content in leaves ($w[N]/10^{-2}$)				
Treatment	0	2	4	6	8
Pinus massoniana shells	2.007 ± 0.061a	1.850 ± 0.014a	1.777 ± 0.097a	2.107 ± 0.026a	2.223 ± 0.196a
Toona sinensis shells	2.143 ± 0.192a	1.890 ± 0.051a	1.740 ± 0.071a	1.897 ± 0.078b	2.357 ± 0.062a
Straight fertilizer	1.940 ± 0.033a	1.850 ± 0.014a	1.807 ± 0.037a	1.860 ± 0.086b	2.357 ± 0.046a

a and b represent α levels at 5%.

Table 9. Wood residue shell slow-release fertilizer and P concentration in eucalyptus tree leaves.

	Content in leaves (w[P]/10^{-2})				
Treatment	0	2	4	6	8
Pinus massoniana shells	0.113 ± 0.005a	0.110 ± 0.001a	0.107 ± 0.009a	0.085 ± 0.004a	0.102 ± 0.014a
Toona sinensis shells	0.127 ± 0.013a	0.098 ± 0.002b	0.095 ± 0.004a	0.082 ± 0.002a	0.102 ± 0.006a
Straight fertilizer	0.110 ± 0.008a	0.107 ± 0.005ab	0.098 ± 0.002a	0.081 ± 0.009a	0.107 ± 0.009a

a and b represent α levels at 5%.

including growth of girth, height, and standing volume. Wood residue shell slow-release fertilizer was found to provide satisfactory release of fertilizer, and *T. sinensis* shells showed slow-release properties superior to those of *P. massoniana* shells.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (31160144) and the Scientific Research and Technology Project of Guangxi (14122005-39). The authors thank the Forestry Science and Engineering Key Laboratory of Guangxi Colleges and Universities for support of this research.

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