Research paper

Methods for Preventing the Invasion of *Leucaena leucocephala* in Coastal Forests of the Hengchun Peninsula, Taiwan

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【Summary】

Leucaena leucocephala, which originates from Central America, has severely invaded the western Hengchun Peninsula and the Penghu Archipelago in Taiwan. This study conducted several physical and chemical control experiments aimed at preventing invasion by this species. Regarding physical control, although adult *L. leucocephala* trees were cut down and new sprouts were cut out once a month for 12 times, sprouting could still not be inhibited. After felling adult trees, the stumps were covered with a thick black plastic sheet. No sprouting occurred in the covered area, yet new sprouts emerged from an uncovered area nearby. Shading treatment using shading nets to reduce the relative light intensity to 5% significantly reduced 63% of the amount and 30% of the length of the sprouts, and rendered *L. leucocephala* seedlings unable to survive. Girdling treatment caused the upper trunk and branches above the girdled area to wither; however, sprouts still grew from the lower edge of the girdled area. Regarding chemical control, smearing herbicide (glyphosate) either on the cut surface of the stumps or on the girdled area of trunks did not inhibit sprouting. However, injection of 3 ml of glyphosate into the trunk of *L. leucocephala* during the dry season considerably inhibited the crown sprouting ratio (to < 10%), but during the rainy season, the injection was less effective (with a sprouting ratio of > 22%). Thus, this study suggests that injection of glyphosate into the trunk is the most effective method to eliminate *L. leucocephala*. However, if herbicide usage is not an option, further investigation could focus on the effectiveness of felling adult trees, shading the stumps, and intensively cutting out new sprouts to inhibit the sprouting of *L. leucocephala*.

Key words: chemical control, girdling, physical control, shading, sprouts.

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研究報告

恆春半島海岸林銀合歡入侵之防治方法

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摘　要

原產於中美洲的銀合歡，在台灣的恆春半島西部及澎湖入侵嚴重。本研究以幾項物理及化學方式對此入侵樹種進行防治試驗。物理防治方面，砍除銀合歡成株後，每個月砍除根株萌蘖一次，經過12次的砍除仍無法抑制萌蘖再生。以黑色厚塑膠布包覆銀合歡根株，被包覆處無法產生萌蘖，但於未包覆處地表仍可長出萌蘖。藉遮陰網將林地相對光量降至5%，可顯著減少銀合歡萌蘖數63%及萌枝長度30%，並令銀合歡種子苗無法存活。將銀合歡樹幹環剝，環剝處上方樹幹會枯死，但環剝處下方卻可長出十幾枝萌蘖，無法令全株死亡。化學防治方面，在銀合歡砍伐後的根株表面塗抹除草劑嘉磷塞，或在樹幹環剝處塗抹該除草劑，都不能抑制萌蘖再生。然而，在銀合歡樹幹鑽孔注射除草劑，於乾季僅施用3 ml即可顯著抑制冠層萌蘖比例(低於10%)，但於雨季期間處理的抑制效果較差(萌蘖比例高於22%)。本研究結果顯示，在樹幹注射除草劑嘉磷塞為消除銀合歡成樹最有效的方法。若不考慮使用除草劑，今後可試驗砍伐銀合歡後將根株遮陰，並密集砍除萌枝，檢驗兼用此兩項處理對抑制銀合歡萌蘖發生的效果。

關鍵詞：化學性防治、環剝、物理性防治、遮陰、萌蘖。

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INTRODUCTION

Leucaena leucocephala (Lam.) de Wit is a small tree or large shrub of the family Mimosaceae. It originates from Central America and was probably introduced to Taiwan in the 16th century by the Dutch and Spanish (Chen and Hu 1976). Before Taiwan underwent economic development, rural residents fed the leaves of *L. leucocephala* to livestock and used its branches as kindling. Therefore, *L. leucocephala* was commonly used, and its population was limited without overexpansion. In the Hengchun Peninsula of southern Taiwan, large areas of native tree species were cut down in the 1950s and replanted with *Agave sisalana*, which was used as raw materials of hemp rope and thus had a high economic value at that time. In 1967, areas planted in *A. sisalana* on the Hengchun Peninsula reached 10,280 ha. However, the advent of nylon ropes reduced the price of *A. sisalana*, and numerous plantations were abandoned, so that by 1986 only 2556 ha of *A. sisalana* remained (Billings 1988). Thereafter, *L. leucocephala* populations rapidly increased on these abandoned farmlands and become large-scale pure stands.

Leucaena leucocephala has heavily invaded the Hengchun Peninsula, and has a wide distribution range (Chung and Lu 2006, Lu and Chung 2007, Wu et al. 2013, Lu 2016). Possible reasons for the success of *L. leucocephala* on the Hengchun Peninsula include the following: (1) it has a high photosynthesis rate and rapid growth (Yang

2011); (2) it forms nodules with nitrogen-fixation capacity and grows in barren habitats (Piggin et al. 1995); (3) the tree can endure dry periods through defoliation (Brandon and Shelton 1993, Jones and Middleton 1995); (4) it has a short juvenile phase; the plant flowers at 4~6 mo old, and can flower and bear fruit throughout the year (Walton 2003); (5) it has an abundant seed production ability; a 2-yr-old tree can produce 4000~6000 seeds at a time (Hutton and Gray 1959, Lee 2003, Walton 2003, Hwang et al. 2010); (6) the plant has strong sprouting ability, and can produce enormous numbers of sprouts after felling, forming a dense crown within a few months (Walton 2003); (7) its leaves and seeds contain minosine and have the potential for plant allelopathy (Chou and Kuo 1986); (8) the plant has few natural enemies in Taiwan that can inhibit its expansion; and (9) because of changes in land-use patterns, large areas of abandoned fields have facilitated the rapid increase in its population. These factors have enabled *L. leucocephala* to become dominant in invaded stands, thus drastically changing the original vegetation composition (Horsley 1977, Lu 2016). Droste et al. (2010) proposed that the reason alien invasive plants succeed is primarily because they genetically possess high morphological and physiological plasticity and can efficiently obtain resources from the environment.

Leucaena leucocephala can easily invade abandoned agricultural and pasture lands. Once it has done so, the original vegetation can be restored only with great difficulty (Walton 2003, Reid et al. 2009). Therefore, restoration of forestlands invaded by *L. leucocephala* requires sufficient ecological knowledge and experience (Wang et al. 2009, 2013). This study focused on 4 physical and 3 chemical control methods to identify effective means of preventing the growth of *L. leucocephala* and suppressing its vigorous sprouting after being felled. The physical control methods used in this study were (1) the continuous cutting of newly growing sprouts, (2) plastic sheet coverage, (3) shading, and (4) trunk girdling, and the chemical control methods were (1) application of herbicides to the cut surface of stumps, (2) smearing of an herbicide on the girdled area of the trunk, and (3) injection of an herbicide into the trunk in different seasons. Any method that can effectively inhibit the growth and sprouting of *L. leucocephala* will substantially aid the ecological restoration of stands invaded by this tree species.

MATERIALS AND METHODS

Study area

The study was conducted in Shanhai Village, Hengchun Township, on the west coast of the Hengchun Peninsula. The experimental site has a tropical climate. According to data from the Hengchun Station of the Central Weather Bureau, the annual mean temperature in this area from 1981 to 2010 was 25.1℃, and the annual rainfall was 2020 mm. Rainfall from November to mid-May represents < 10% of the annual rainfall, and the dry season lasts for 6 mo. The northeast monsoon prevails from October to March each year. When the monsoon passes through the Central Mountain Range to the west coast of the Hengchun Peninsula, a downdraft forms (foehn winds), which causes the atmosphere and soil to dry out.

Treatments for inhibiting sprouts after felling *L. leucocephala*

Herbicide application and physically covering stumps

On 17 May 2008, a secondary forest of *L. leucocephala* in the Shizhu area of Shanhai Village was felled with a chainsaw. On the day following the felling operation, the stumps were treated with 2 methods: (1) herbicide application using glyphosate (41%, undiluted stock solution) and (2) covering the stumps with a thick black plastic sheet. For the first method, we used a brush to smear 0.8~1.0 ml of glyphosate over the cut stump surface. Untreated stumps were used as a control. The 2 treatments and the control consisted 30 individual stumps each. The number of sprouts and the lengths of the 3 longest sprouts of each stump were measured at 1 and 2 mo after treatment. In addition, the proportion of sprouting plants of all stumps was calculated.

Continuous cutting of newly growing sprouts

After deforestation of another adjacent stand of *L. leucocephala* at the Shizhu experimental site in August 2008, 30 stumps were labeled. One month later (in September), the number of sprouts and the lengths of the 3 longest sprouts were measured. The new sprouts were then cut off at the base and measured again after 1 mo. This procedure was repeated each month until September 2009, with the exception of January 2009; therefore, data for February 2009 represents 2 mo of growth. During the experiment, new sprouts were cut a total of 11 times, and the number and length of new sprouts were measured 12 times. We selected 36 newly growing sprouts of various lengths and measured the leaf area of the sprout, thereby establishing a regression equation of length vs. leaf area. Counting the number of sprouts that emerged within 1 mo from each stump and their lengths, we could estimate the total leaf area produced in 1 mo by each stump.

Stump shading treatment

After the secondary forest of *L. leucocephala* at the Shizhu experiment site was felled in August 2008, most of the stumps sprouted. In May 2010, a shading net was placed over the stumps of felled *L. leucocephala* at 2 plots. The shading net was set at 1.5 m in height, it was 10 m long and 2 m wide, and covered a total area of 20 m^2. Support stands were built to cover the area using 1 or 2 layers of shading nets. The light transmittance of the shading net was 20%. The control plot was adjacent to the shaded plots and was marked off with a nylon rope, also comprising an area of 20 m^2. This unshaded plot was not covered and served as a full-light control. After the shading nets were set up, the light intensity in the 3 plots was measured using a quantum sensor (LI-190, LI-COR, Lincoln, NE, USA) and data logger (LI-1400, LI-COR). Four quantum sensors were placed in each of the 2 shaded plots and the full-light control plot at a height of 30 cm above the ground, with an interval of 2 m between sensors. The data loggers recorded the light intensity at 1-min intervals over 7 consecutive days. Data from 10:00 to 14:00 on 2 sunny days were selected to calculate the relative light intensity of the shaded plots during the same period. According to the results, the relative light intensities under the 1-layer and 2-layer shaded plots were 32 and 5%, respectively, of the control plot. At the beginning of the experiment, 22 stumps were marked in each of the 3 sampling plots, and sprouts that had grown from these stumps were removed. After shading treatment, the number of and length of new sprouts were measured every 2 wk, and the number of seedlings growing from *L. leucocephala* seeds in each sampling plot was calculated.

Girdling of adult *L. leucocephala*

In May 2009, 2 types of girdling treatments were conducted on a secondary forest stand near Shanhai Village. Twenty individuals of *L. leucocephala* with a mean diameter at breast height (DBH) of 5.4 cm were randomly selected for treatment. The 2 treatments were (1) trunk girdling with a width of 20 cm at 130 cm above the ground, with no herbicide application, and (2) immediately after the same treatment, the girdled area was smeared with 1.0~1.4 ml of glyphosate. The proportion of withered upper stems of all treated individuals, the number of sprouts per tree, and the mean length of the 3 longest sprouts were calculated monthly for 3 mo after girdling treatment.

Chemical injection treatment

The chemical injection experiment was conducted at Binlangkeng in Shanhai Village every 2 mo from October 2009 to October 2010, for a total of 7 times. Each time, 20 *L. leucocephala* adult trees with a DBH of 5~8 cm were randomly selected. An electric drill was used to drill a hole approximately 3 cm deep in the trunk at a height of 120 cm, and 3 ml of glyphosate was injected into each hole with a plastic syringe. One hole was drilled in each tree. After injection, the surface of the hole was filled with silicone. The ratio of new sprouts to the whole crown after treatment was recorded biweekly using the following procedure. We photographed the tree crown of each individual before treatment. All leaves of this individual consequently fell out after treatment. Then, the tree crown was photographed every 2 wk thereafter. The proportion of new sprouts of the original tree crown, i.e., the sprouting ratio, at each stage was estimated.

RESULTS

Treatments for inhibiting sprouts after felling *L. leucocephala*

One month after felling *L. leucocephala*, 98% of the control stumps had produced an average of 25 sprouts, and the average length of the 3 longest sprouts was 49 cm. After 2 mo, the average sprout length of control stumps had increased to 121 cm (Table 1). Of the sprout-inhibition treatments, the herbicide application method exhibited an optimal inhibitory effect. Only 8% of stumps developed sprouts in the first month after this treatment, and new leaves on the sprouts had an abnormal appearance. At 2 mo after treatment, the proportion of sprouting stumps had increased to 31%, with an average number of

Table 1. Inhibition of sprout production by herbicide application and plastic sheet coverage of stumps of *Leucaena leucocephala* (*n* = 30)

Treatment	1 mo after treatment			2 mo after treatment		
	Proportion of sprouting stumps	Number of sprouts per stump	Average length of the 3 longest sprouts (cm)	Proportion of sprouting stumps	Number of sprouts per stump	Average length of the 3 longest sprouts (cm)
Control	98%	$25 \pm 2^{a,1)}$	49 ± 7^{a}	98%	19 ± 3^{a}	121 ± 19^{a}
Herbicide application on stump	8%	1 ± 0^{c}	7 ± 3^{b}	31%	14 ± 1^{b}	64 ± 6^{b}
Plastic sheet coverage	75%	5 ± 1^{b}	0.9 ± 0.3^{c}	73%	9 ± 2^{c}	105 ± 4^{a}

1) Different letters indicate a significant difference among treatments ($p < 0.05$, by Duncan's test).

14 sprouts per stump and an average length of 64 cm (Table 1). This indicated that applying herbicide to stumps only once could not completely kill *L. leucocephala*; 31% of the stumps were able to gradually resume growth. After treatment by covering the stumps with a thick plastic sheet, 75% of the stumps had grown sprouts after 1 mo, although the length of these sprouts was < 1 cm (Table 1). At 2 mo after treatment, 73% of the stumps could still grow sprouts, and the average number of sprouts was 9. However, the average length of the sprouts exceeded 100 cm (Table 1).

Regarding the method of cutting newly growing sprouts each month, each stump respectively grew 20 and 19 sprouts in the first and second months (Fig. 1). Subsequently, after continued monthly cutting, each stump grew 13~19 sprouts. At the 11th cutting (in September 2009), the average monthly number of sprouts still reached 10 (Fig. 1A). In the first month after the felling of *L. leucocephala* (in September 2008), the average length of the 3 longest sprouts was only 29 cm (Fig. 1B), and the mean total leaf area per stump was 370 cm^2 (Fig. 1C). These sprouts were cut again, and after 1 mo (in October 2008), the average length of the 3 longest new sprouts was 75 cm, and the leaf area had increased to 1100 cm^2. After October 2008,

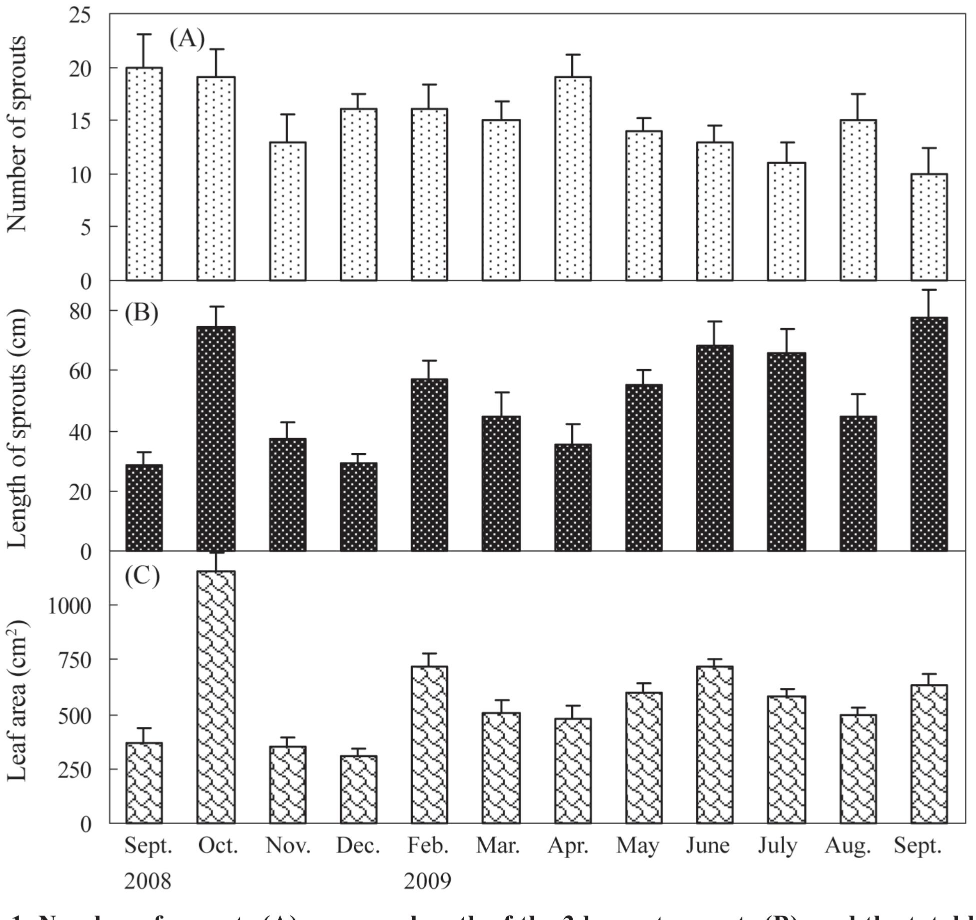

Fig. 1. Number of sprouts (A), average length of the 3 longest sprouts (B), and the total leaf area (C) of *Leucaena leucocephala* stumps treated by cutting sprouts every month (n = 30).

the length of newly growing sprouts ranged mainly from 30 to 70 cm with a total leaf area of 300~600 cm^2; however, after 11 consecutive cuttings, newly growing sprouts could still grow to 77 cm in 1 mo (Fig. 1B, C).

After 6~16 wk of shading treatment, no significant difference in the average number of sprouts was found for the 5 and 32% relative light intensity plots. However, the number of sprouts on the 5% shaded stumps was significantly reduced to 37% compared to the unshaded control (Fig. 2A). During the first 2~6 wk of shading treatment, the lengths of sprouts in the 2 shading treatments did not significantly differ from that of the control. However, in the 16^{th} wk of shading treatment, average sprout lengths under the 5 and 32% shaded plots were 89 and 112 cm, respectively, which were significantly lower than that of the control plot (127 cm) (Fig. 2B). These results indicated that reducing the light intensity to 5% could inhibit 63% of the amount and 30% of the length of the sprouts. Under the 5% relative light intensity, the density of naturally regenerating *L. leucocephala* seedlings was very low and had become 0 by the 16^{th} wk (Fig. 2C). Under the 32% relative light intensity, the density of naturally regenerated *L. leucocephala* seedlings also continued to decrease from the 6th to the 16^{th} week (Fig. 2C). In contrast, the density of *L. leucocephala* seedlings in the control plot increased from 7 to 41 stems m^{-2} from the 2^{nd} to the 6^{th} weeks after treatment, and then decreased. In the 16^{th} wk of treatment, the seedling density was still 6 seedlings m^{-2}, which was higher than those of the 2 shading treatment plots (Fig. 2C). These results indicated that a shaded environment could inhibit seed germination and survival of *L. leucocephala* seedlings.

Girdling treatment

The trunk of *L. leucocephala* plants was girdled to a width of 20 cm. After 1 mo, the crown layer of only 1 girdled *L. leucocephala* was found to have completely withered, whereas 19 of them were unharmed. However, upper growth of 16 and 17 girdled *L. leucocephala* was completely dead at 2 and 3 mo after treatment, respectively, and mortality rates were 80 and 85% (Fig. 3A). Although girdling treatment was able to kill most of the upper growth, numerous sprouts emerged from the lower edge of the girdling area a short time after treatment. At 1 mo after treatment, the average number of such sprouts was 11, and their average length was 22 cm, with the longest one at 45 cm (Fig. 3B). At 3 mo after treatment, the average length of these sprouts was more than 100 cm (Fig. 3C). These results indicated that when the trunks of *L. leucocephala* were girdled at a height of 130 cm above the ground, most of the upper growth (above the girdled area) died, but many new branches still sprouted below the girdled area, and the treatment did not entirely kill the trees.

The second treatment method applied undiluted glyphosate to the girdled area after girdling the trunks. In the first month after treatment, the upper branches of 19 trees were found to have become completely defoliated, whereas 1 tree remained intact, with no defoliation (Fig. 3A). In the third month after treatment, the upper trunks of 20 trees (100%) had completely died. However, 3 mo after the stumps were treated with girdling and herbicide, the average number of sprouts below the girdled area was 13, with an average length exceeding 100 cm (Fig. 3B,C). Therefore, although this treatment was able to kill the upper trunk, it did not inhibit sprouting below the girdled area.

Chemical injection

Leucaena leucocephala was chemically

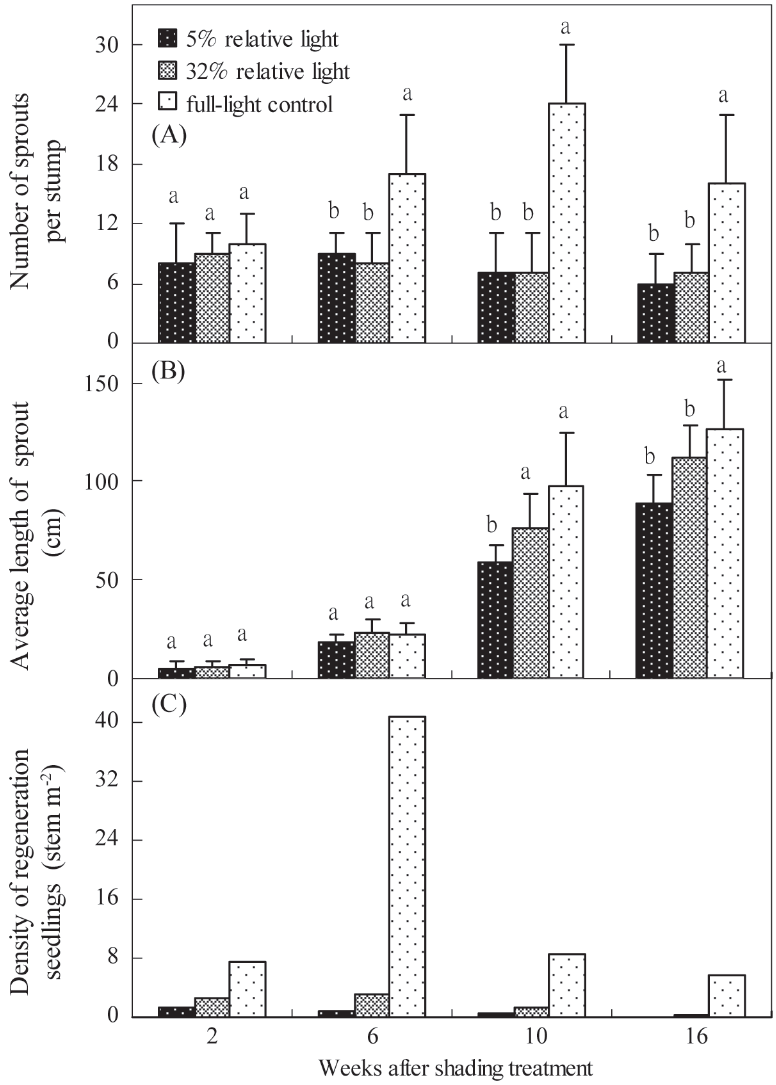

Fig. 2. Number of sprouts per stump (A), average length of the 3 longest sprouts (B), and density of naturally regenerated seedlings (C) of *Leucaena leucocephala* under different shading conditions. Different letters indicate a significant difference among the shading treatments (p < 0.05, by Duncan's test).

injected in different months of the year, and each tree was found to have become defoliated within 2 wk of treatment, with an extremely small number of new sprouts (Table 2). Of the 7 treatments during the year, plants treated in the rainy season (June and August) sprouted earlier, whereas those treated in other months required an additional 8 wk to sprout (Table 2). The sprouting ratio in the 8th wk after treatment was lowest for the October and December applications, with sprouting ratios of as low as 3.0~9.7%. However, if the injection was applied in June or August, then the sprouting rate reached 24.6~22.8%, indicating a weaker inhibitory effect (Table 2). These results demonstrated that employing

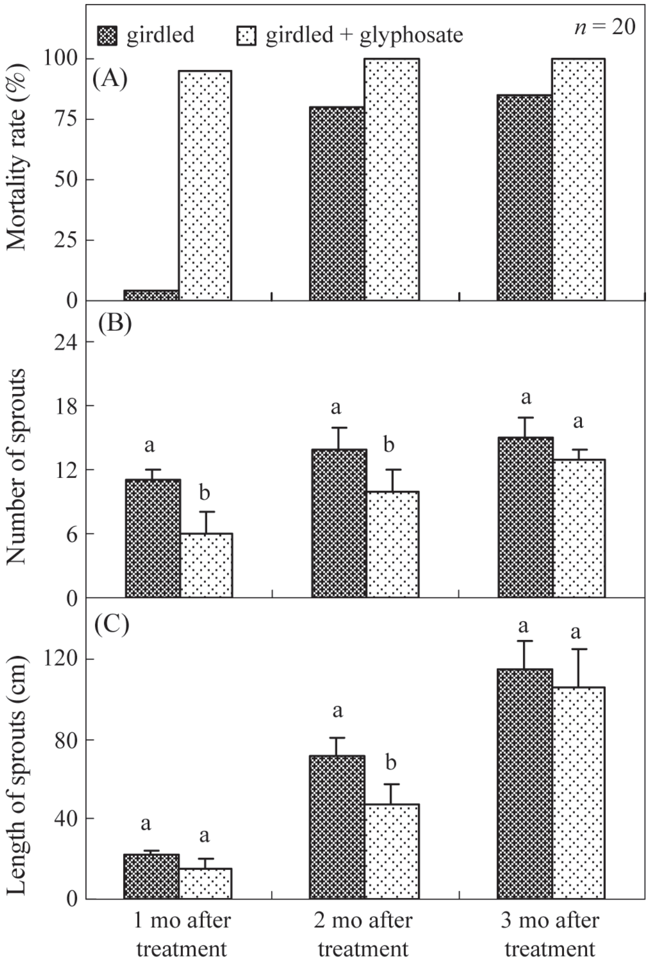

Fig. 3. Mortality rate of the upper trunk (A), number of sprouts per tree (B), and the average length of the 3 longest sprouts (C) of *Leucaena leucocephala* after girdling treatment. Different letters indicate a significant difference among girdling treatments ($p < 0.05$, by a t-test).

chemical injections in the early dry season could substantially reduce the sprouting of *L. leucocephala*.

DISCUSSION

Leucaena leucocephala exhibits a high capacity for vegetative reproduction. After felling, numerous sprouts will reemerge from the stumps, causing a predicament for control efforts. On the west coast of the Hengchun Peninsula, these sprouts can form dense pure stands, flowering, fruiting, and dispersing seeds in a year (pers. observ.). Therefore, preventing stumps from sprouting is the primary task for controlling *L. leucocephala*. This study found that *L. leucocephala* stumps could still grow more than 10 new sprouts after the previous ones were cut off. Even with continuous cutting operations, the number and length of the sprouts did not decrease, indicating that the vitality of *L. leucocephala*

Table 2. Sprouting rates (%) at various times after injection of 3 ml of glyphosate into the trunk of *Leucaena leucocephala* (*n* = 20)

Date of injection	2 wk after treatment	4 wk	8 wk	16 wk	24 wk
2009					
October	0.0[c,1)]	0.0[b]	3.0±1.7[d]	0.8±0.3[d]	6.4±1.3[c]
December	0.0[c]	0.0[b]	9.7±2.6[c]	14.8±1.9[c]	26.5±4.2[b]
2010					
February	0.0[c]	0.0[b]	14.3±1.1[b]	20.3±2.2[b]	46.4±5.8[a]
April	0.0[c]	0.0[b]	15.0±2.3[b]	28.4±3.7[a]	48.2±6.1[a]
June	0.3±0.1[b]	16.8±2.4[a]	24.6±3.6[a]	30.5±4.1[a]	-[2)]
August	1.0±0.2[a]	15.4±1.8[a]	22.8±4.1[a]	-	-
October	0.0[c]	0.0[c]	-	-	-

1) Different letters in the same week among treatment dates indicate a significant difference ($p < 0.05$, by Duncan's test).

2) The experiment ended, and no data were collected thereafter.

was not diminished by merely cutting off sprouts once a month. The reason for continuous sprouting might be due to sufficient energy being stored in its subsurface root system (Aubrey and Teskey 2018). Another reason might be that the photosynthetic capacity of its new leaves is very high after sprouting (Yang 2011). Net photosynthetic rates of *L. leucocephala* sprouts during the dry season (March) and rainy season (September) were 23.4 and 28.7 μmol CO_2 m^{-2} s^{-1}, respectively (unpubl. data). This high level of photosynthesis, plus 300~600 cm^2 of leaf area produced each month, indicated that the new leaves of sprouts could generate large amounts of carbohydrates within a short time and store these products in the plant. Thus, if the sprouts were cut off, the plant still had enough energy to grow new sprouts. We hence suggest that the sprouts should be cut off immediately after emerging, so that their new leaves have no time to synthesize carbohydrates. The energy stored in the root system can thus be exhausted, and the trees will die.

A shaded environment can inhibit the germination of seeds and growth of *L. leucocephala* seedlings (Wang et al. 2009). Piggin (1995) found that the minimum relative light intensity required by *L. leucocephala* seedlings was approximately 35%. In this study, shading nets were used to cover *L. leucocephala* stumps, which simulated the light environment after crown closure. In a low-light environment of 32 or 5% relative light intensity, seedling density as well as both the number and length of stump sprouts were all lower than those in a full-light environment. The light compensation point of *L. leucocephala* leaves was measured at 22~28 μmol photon m^{-2} s^{-1} (unpubl. data). This result indicated that in an environment with a light intensity of < 20 μmol photon m^{-2} s^{-1}, the net photosynthetic rate of *L. leucocephala* sprouts would be substantially inhibited. Ten weeks after establishing a shaded environment at the experimental site, the seedling density of *L. leucocephala* continued to decrease, whereas the seedling density in the full-light plot had considerably increased. This indicated that the *L. leucocephala* seed bank in the soil could not germinate in a low-light environment, nor could its seedlings grow and survive in such an environment.

Girdling is another method used to inhibit the growth of invasive tree species. In Hawaii Volcanoes National Park (USA), Loh and Daehler (2008) used trunk girdling to control the invasive tree species *Morella faya*, and found that girdling caused this tree to die. Removing the crown of an invasive tree species can create large gaps in a short time, thus possibly causing an adverse effect of reinvasion by light-demanding tree species. With girdling treatment, invasive trees do not need to be removed; and light resources in the forest gradually increased to enable the reestablishment of local native plants. In this study, the trunk of *L. leucocephala* was girdled to a width of 20 cm at a height of 1.3 m above the ground. At 2 to3 mo after treatment, the upper trunk of most of the plants had died, yet after 1 mo, numerous sprouts had already grown from the lower edge of the girdled area. If girdling treatment was deployed at the base of the trunk, the shading created by the upper crown of *L. leucocephala* might be reduced, and thus be beneficial to the growth of desired native tree species. However, girdling *L. leucocephala* was not an easy task and was time-consuming; for example, girdling an individual with a DBH of 5~6 cm took approximately 5~10 min. Therefore, girdling treatment is not practical for killing a large stand of *L. leucocephala*. In this study, we further applied an herbicide (glyphosate) to the girdled area. Although this treatment caused defoliation on all of the treated trees, sprouts still grew at the lower edge of the girdled area. In sum, girdling with or without applying glyphosate could not kill the entire *L. leucocephala* tree.

Other research removed the roots after felling or girdling *L. leucocephala* to prevent sprouting. Walton (2003) suggested using a blade plough to remove the root system of *L. leucocephala* and prevent its roots from sprouting again. In South Africa, *L. leucocephala* was completely removed using this method (Walton 2003). However, this type of machinery is only suitable for use on agricultural or pasture land. Heavy machinery might not even be able to enter forested areas. Its operation would seriously compress the forest soil, destroy the soil structure, increase soil erosion, and could also cause secondary plant invasion (Pearson et al. 2016). González et al. (2017) and Sher et al. (2018) reported that removing invasive plants by means of heavy machinery severely disturbed forestlands and delayed the recovery rate of native plants.

Chemical methods are economical and effective in controlling invasive plants. Commonly used chemicals, such as glyphosate, Access®, and Lontrel®, have less impact on the environment and can effectively kill target plants (Walton 2003, Wang and Hung 2005, Chen et al. 2008). On the Hengchun Peninsula, Wang and Hung (2005) injected glyphosate into severely invasive *L. leucocephala* stands, using various doses (7.5~10.5 ml) according to the DBH, and achieved a fatality rate of up to 100%. In this study, each *L. leucocephala* stem was injected with only 3 ml of glyphosate. Although the upper growth defoliated and withered following the injection, some of the trees did not die, and sprouts continued to grow from their trunks. The effect of injecting herbicides during the dry season was found to be more favorable than during the rainy season. Injecting the herbicide in the beginning of the dry season resulted in the smallest sprouting ratio and a greater number of deformed leaves. Future control measures should consider local rainfall conditions and undertake treatment during relatively dry periods to increase the success of control measures. Glyphosate, the herbicide used in this study, is frequently used in the United States and Australia to prevent invasive woody plants because it is effective and has a short soil residence time (Walton 2003, Wang and Hung 2005). In the Hengchun coastal forest, Chen et al. (2008) found that the soil residence time of this chemical decreased to ppm levels within 1 yr of its injection, and that injection during summer could reduce the degradation time of glyphosate and possible soil contamination. In addition to injections, smearing the herbicide on the cut surface can also effectively inhibit the sprouting of invasive woody plants. For instance, to control 2 invasive Tamarix tree species, the trees were cut down, systemic herbicides were applied to the cut surface of the stumps, and the sprouts were effectively inhibited (Sher et al. 2018). In this study, glyphosate was applied to the cut surface of *L. leucocephala* stumps in May (the rainy season), but this did not kill the tree. It might be because rain had diluted or washed away the glyphosate. If applied a second time or during the dry season, the inhibitory effects of the herbicide might have been more significant.

Although shading cannot completely block the emergence of *L. leucocephala* sprouts, it can reduce light resources to the new sprouts and hence reduce their growth rate. In this study, the experiment of continuous cutting of *L. leucocephala* sprouts every month was conducted under a full-light environment with no shading. If the cutting had been carried out under a shaded environment, the vitality of the sprouts should be greatly diminished. The shading treatment of this research used shading nets to lower the light resources. This kind of shading operation is only applicable within small areas of a forestland, while not suitable for large-scale forestlands. However, if a naturally shaded environment which is created by surrounding vegetation could be in synergy with the artificial cutting of new sprouts, the growth of *L. leucocephala* new sprouts would be greatly inhibited. This type of natural shading could be accomplished by ecological restoration. An experiment was conducted to control *L. leucocephala* through ecological restoration in a coastal forest of the Hengchun Peninsula (Chen et al. 2011, Wang et al. 2013). In that experiment, a hand-held chainsaw was used to cut down adult trees of this species through a strip-logging approach. After the felling operation, the forestland was immediately planted with 17 native tree species including 11 fast-growing species. After 2 yr of ecological restoration, the dominance of *L. leucocephala* had been inhibited, and the diversity of the native tree species in this forest had continued to increase (Chen et al. 2011). In the current study, chemical injection was found to be the most effective method to eliminate *L. leucocephala* and prevent it from sprouting. However, if herbicide application cannot be considered for the sake of environmental protection, then the ecological restoration of fast-growing native trees, plus continuous cutting of new sprouts, might also achieve the goal of preventing the regrowth of this species.

CONCLUSIONS

This study surveyed 4 methods to inhibit sprouting from stumps of felled *L. leucocephala* trees, and 3 methods to cause adult trees to lose vitality. Covering the stumps or smearing herbicide on the surface of the stumps did not provide the expected inhibitory results. Cutting new sprouts from the stumps once a month under a full-light environment was also ineffective. Although a shaded environment could not restrain sprouting, the number and length of sprouts were significantly reduced. In addition, shading can effectively diminish the number of seedlings germinating from *L. leucocephala* seeds and their survival. For the purpose of eliminating *L. leucocephala* adult trees, girdling with or without herbicide smeared on the girdled area can only kill the upper stem but not the lower portion. Injection of an herbicide into the trunk was found to be the most effective method to kill adult trees. During the dry season, only 3 ml of herbicide was needed to kill a tree.

LITERATURE CITED

Aubrey DP, Teskey RO. 2018. Stored root carbohydrates can maintain root respiration for extended periods. New Phytol 218:142-52.

Billings BH. 1988. Program for restoration of the Hengchun sisal station as a historical monument. Conservation Report no. 39. Pingtung, Taiwan: Kenting National Park. 77 p.

Brandon N, Shelton HM. 1993. The role of vesicular-arbuscular mycorrhizae in *leucaena* establishment. Proceedings of XVII International Grassland Congress; 1993 Feb 8-21; Palmerston North, New Zealand: New Zealand Grassland Association. p 2064-5.

Chen KF, Wu SH, Wang HH, Kuo YL. 2011. First two years' growth performances of planted tree seedlings for ecological restoration on west coast of Hengchun. J Natl Park 21(4):63-72. [in Chinese with English summary].

Chen RF, Wang HH, Wang CY. 2008. Dissipation of glyphosate injected into the lead tree (*Leucaena leucocephala*) in different seasons in Taiwan. Taiwan J For Sci 23(4):289-99.

Chen TS, Hu TW. 1976. A list of exotic ornamental plants in Taiwan. Taipei, Taiwan: Taiwan Forestry Research Institute. 618 p. [in Chinese].

Chou CH, Kuo YL. 1986. Allelopathic research of subtropical vegetation in Taiwan. J Chem Ecol 12:1431-48.

Chung YL, Lu ML. 2006. Using SPOT imagery to map the invasive distribution of *Leucaena leucocephala* in Kenting National Park. Taiwan J For Sci 21:167-77. [in Chinese with English summary].

Droste T, Flory SL, Clay K. 2010. Variation for phenotypic plasticity among populations of an invasive exotic grass. Plant Ecol 207:297-306.

González E, Sher AA, Anderson RM, Bay RF, Bean DW, Bissonnete GJ, et al. 2017. Vegetation response to removal and biocontrol of invasive *Tamarix* in southwestern U.S. rivers: a collaborative study including 416 sites. Ecol Appl 27:1789-804.

Horsley SB. 1977. Allelopathic interference among plants. II. Physiological modes of action. Proceedings of the 4th North American Forest Biology Workshop; 1976 Aug 9-11; New York: Univ. of New York. p 93-136.

Hutton EM, Gray SG. 1959. Problems in adapting *Leucaena glauca* as a forage for the Australian tropics. Empir J Exp Agric 27:187-96.

Hwang CY, Hsu LM, Liou YJ, Wang CY. 2010. Distribution, growth, and seed germination ability of lead tree (*Leucaena leucocephala*) plants in Penghu Islands, Taiwan. Weed Tech 24:574-82.

Jones RJ, Middleton C. 1995. Leucaena survives drought in central Queensland. LEUCNET News 2:6-7.

Lee JT. 2003. Study on the spread and invasion of *Leucaena leucocephala* in Hengchung area [MSc thesis]. Pingtung, Taiwan: National Pingtung Univ. of Science and Technology. 70 p. [in Chinese with English summary].

Loh RK, Daehler CC. 2008. Influence of woody invader control methods and seed availability on native and invasive species establishment in a Hawaiian forest. Biol Invasions 10:805-19.

Lu ML. 2016. Modeling the population expansion of an alien-invasive species (*Leucaena leucocephala*). J Photo Remote Sens 21(2):65-74. [in Chinese with English summary].

Lu ML, Chung YL. 2007. Spatial distribution pattern of *Leucaena leucocephala* in the Kenting National Park. Endem Spec Res 9(2):7-18. [in Chinese with English summary].

Pearson DE, Ortega YK, Runyon JB, Butler JL. 2016. Secondary invasion: the bane of weed management. Biol Conserv 197:8-17.

Piggin CM, Shelton HM, Dart PJ. 1995. Establishment and early growth of *Leucaena*. Canberra, Australia: ACIAR Proceedings no. 57, p 87-93.

Reid AM, Morin L, Downey PO, Frenchand K, Virtue JG. 2009. Does invasive plant management aid the restoration of natural ecosystems? Biol Conserv 142:2342-9.

Sher AA, Waer HE, Gonzáleza E, Anderson R, Henry AL, Biedron R, et al. 2018. Native species recovery after reduction of an invasive tree by biological control with and without active removal. Ecol Eng 111:167-75.

Walton C. 2003. Leucaena (*Leucaena leucocephala*) in Queensland. Queensland, Australia: Department of Natural Resources and Mines. 51 p.

Wang HH, Hung SF. 2005. The effect of herbicide injection on *Leucaena* control and techniques of forest restoration. Weed Sci Bull 26(1):15-32. [in Chinese with English summary].

Wang HH, Hung SF, Kuo YL, Chen FH. 2009. A survey on the early growth of seedlings in restored tropical coastal forest invaded by *Leucaena leucocephala* in southern Taiwan. J Natl Park 19(1):9-22. [in Chinese with English summary].

Wang HH, Kuo YL, Chen FH. 2013. Operation techniques of ecological rehabilitation on the *Leucaena leucocephala* invaded stands. Taipei, Taiwan: Taiwan Forestry Research Institute. 24 p. [in Chinese].

Wu KJ, Ho YW, Chen JC, Chen CT. 2013. The relationship between landscape change and invasion of *Leucaena leucocephala* in Kenting National Park. J Natl Park 23(4):32-41.

Yang YP. 2011. Comparison in predawn leaf water potential and photosynthetic capacity between dry and wet season in saplings of ten tree species inhabit at west coast of Hengchun, Taiwan [MSc thesis]. Pingtung, Taiwan: National Pingtung Univ. of Science and Technology. 63 p. [in Chinese with English summary].