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# Growth of Trees Planted for Rehabilitation of a Saline Area of the Wheatbelt in Western Australia

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## Abstract

We clarified the relationship between environmental factors and the growth of seven *Eucalyptus* species and *Casuarina obesa* planted at an afforestation site in southern Western Australia's wheatbelt. The site consisted of abandoned fields damaged by secondary salinity associated with waterlogging. Afforestation is expected to progressively rehabilitate the land, which has a slight slope generating a large environmental gradient. During the rainy season, waterlogging (soil becoming saturated with water) occurred at the lower part of the site, but not at the higher part. The level of salt in the soil ($EC_{1:5}$) increased gradually from higher to lower ground (0.34—2.7 dS $m^{-1}$). Tree size and growth rate were negatively related to waterlogging intensity and showed small values at the lower part of the site, with only a slight effect on tree size and growth rate. Moreover, interspecific differences in size and growth rate were observed. *Eucalyptus sargentii* and *E. occidentalis* had larger sizes and faster growth rates than *E. camaldulensis*. Trees planted under waterlogging conditions at the lower part of the site are likely to fail due to poor growth; therefore, afforestation should begin on higher ground where trees would experience normal growth, and in doing so, reduce the soil water content to rehabilitate the land. Improvement of water balance through afforestation would confirm the benefits of appropriate agroforestry management.

**Discipline:** Agricultural environment
**Additional key words:** abandoned field, agroforestry, waterlogging

## Introduction

The wheatbelt in southern Western Australia is about 300 km wide and is primarily used for cultivating wheat and raising livestock. Recently, however, secondary salinity associated with waterlogging has reduced land productivity, leading to the serious problem of abandoned fields[6]. Almost all Australian crop fields were previously covered with eucalypt woodlands[3]. As a consequence of settlement by people of European ancestry, these woodlands were cleared and converted to agricultural land, especially over the last century. Conversion from deep-rooted perennial woodlands to shallow-rooted annual crops has resulted in substantially decreased transpiration by vegetation and rising groundwater tables[18,19]. Increased evaporation from the ground surface has led to the accumulation of salt. Salinity is closely associated with waterlogging and both lead to land degradation, a problem throughout Australia, especially in Western Australia's vast croplands. As a result of conversion from the natural vegetation to the present vegetation, the estimated decrease in biomass around the wheatbelt in Western Australia is the largest in Australia[7]. Deterioration of the hydrological ecosystem balance due to changes in land use is severe in Western Australia. In 1996, the total area of human-induced salt-affected land in Western Australia was

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18,040 km$^2$, which then corresponded to more than 70% of the total salt-affected land in all of Australia[11]. Moreover, the predicted increase in salt-affected land suggests that the total affected area will reach 88,000 km$^2$ by 2050[15].

Excess salt hinders osmotic control of plants and inhibits water use. The occurrence of waterlogging results in stomatal closure, reduced photosynthetic rate, and suppressed growth[16]. Moreover, oxygen in the soil is consumed so quickly that the plant roots suffer from anoxia. The soil reaches a state under lack of oxgen, which causes damage to plant roots. The symptoms of salt damage differ according to microtopography. On low ground and in hollows, the combined damage from salinity and waterlogging is extensive. Salinity damages not only agriculture, but also the quality of water for other uses, posing an urgent societal problem that must be resolved[6,8]. In view of these effects of excess salinity and waterlogging, afforestation of damaged fields may be effective in preventing or reducing this damage[4,5]. However, although afforestation of a large area would effectively rehabilitate fields abandoned due to significant salt accumulation, heavy waterlogging, or both, this is not an easy practice, mainly for economic reasons. For efficient rehabilitation, the selection of tree species should be based on superior resistance to salt and waterlogging stress. In the case of planting trees for the purpose of ecosystem conservation, endemic species are preferable, because they are somewhat more tolerant to environmental stress in their own habitat.

This study aimed to elucidate the relationships between microenvironmental factors and the growth of afforestation trees in an abandoned field that was conspicuously damaged by salinity coupled with waterlogging. We investigated

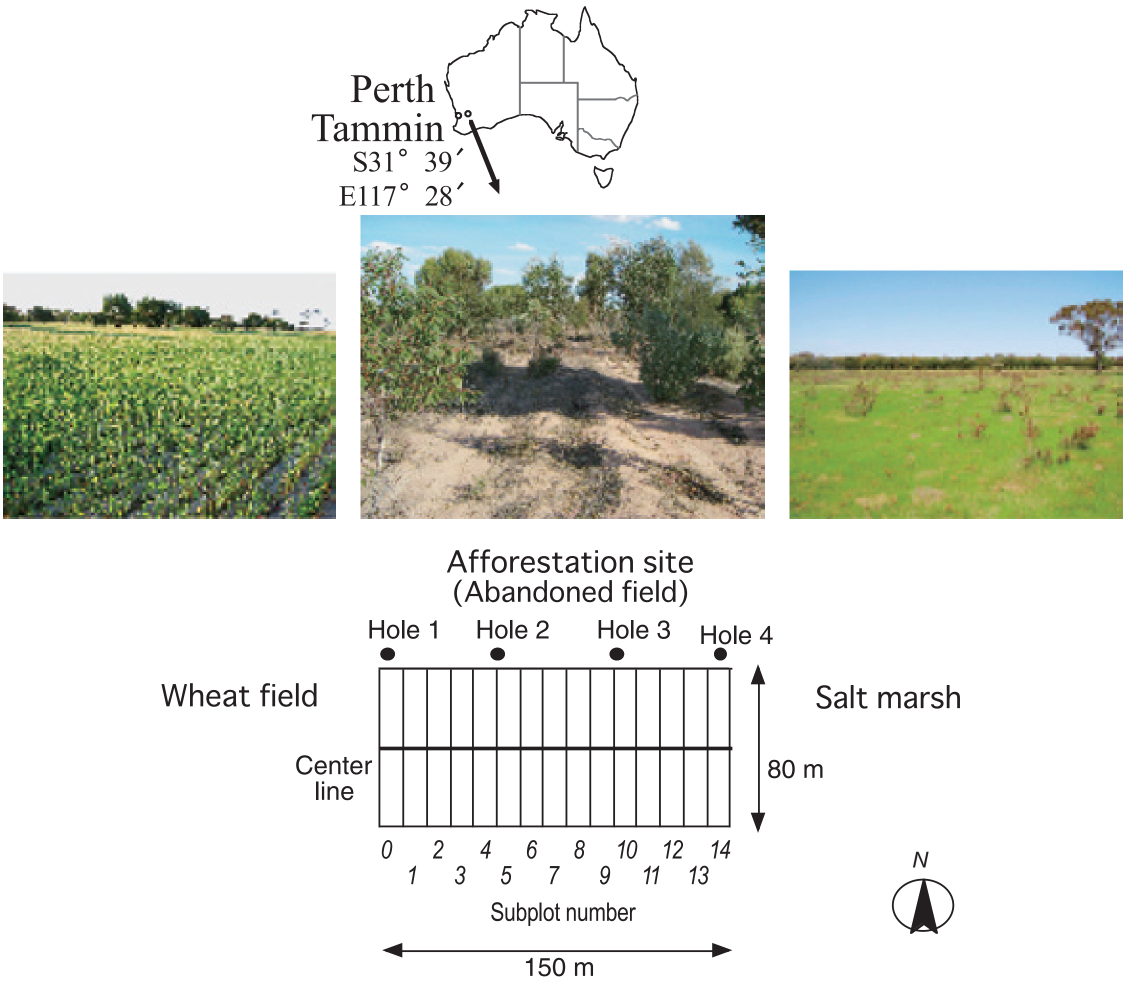


**Fig. 1. Outline of research site**

Tammin is located inland, about 200 km from Perth, the capital of Western Australia. The rectangular research plot was set up in a woodlot adjacent to a wheat field abandoned due to salinity and waterlogging. The plot was divided into 10 m × 80 m subplots, and numbered starting from the western side. The ground level and soil EC values were measured along the center of the plot. Soil water sensors were installed 0.1, 0.5 and 0.8 m deep in holes 1, 2, 3, and 4.

*Eucalyptus* trees and *Casuarina obesa*, which are both species endemic to Western Australia. We separated the effects of salinity and waterlogging on these afforestation trees and constructed a plan for rehabilitation of the agricultural land ecosystem. We examined ground-level topology, soil properties (electrical conductivity as a measurement of the salinity level and water content as an indicator of waterlogging), and growth of trees. We clarified the relationship between size and growth rates of trees and two environmental factors: salinity and waterlogging. Based on the results, we propose guidelines that include several measures for preventing and repairing salinity damage and ensuring sustainable use of agricultural land and rehabilitation of abandoned fields.

## Methods

The study site was Tammin, located inland in the central wheatbelt in southern Western Australia (S31°39’, E117°28’, Fig. 1), about 200 km east of Perth. Average monthly maximum air temperature is 34°C in January, and the minimum is 6.1°C in August; annual precipitation is about 350 mm[1]. The area has a Mediterranean climate with a rainy season in winter, May to August, and is relatively dry in summer, November to February. Farmland, primarily used for cultivating wheat and raising livestock, extends throughout this region and consists of gently undulating plains. We set up a research plot measuring 150 m × 80 m on an afforestation woodlot adjacent to a wheat field that was on lower ground than the surrounding crop fields and had been abandoned about 10 years ago (Fig. 1). At the west side of the plot, near the wheat field, trees were planted about 10 years ago according to the property owner, and the height of the trees was around 5 m. Detailed records about trees planted there have been lost. There are also some halophytes on the east side of the plot. A salt marsh spreads far to the east from the eastern edge of the plot. In the plot, clay soil is prominent, and the ground is muddy in the wet season and very hard in the dry season. Trees had been planted from the adjacent wheat field to the north and south using a heavy-duty tree planting machine.

We set up 15 subplots measuring 10 m × 80 m and numbered them from 0 to 14 starting with the westernmost subplot (Fig. 1). Seven species belonging to *Eucalyptus* were planted, as well as *Casuarina obesa* and *Acacia saligna*. These species are endemic to Australia and are somewhat tolerant to salinity. As *A. saligna* was short lived, small and already showing some dieback near the beginning of the study, we excluded it from further study. On September 15, 2005, we identified the species of planted trees and measured their girth at 0.3 m in height and the total tree height ($H$ in m) for all *Eucalyptus* and *C. obesa*. The second measurement was carried out one year later. The girth at 0.3 m in height was converted to diameter ($D$ in m). We then calculated $D^2H$ ($m^3$) as the size of each plant and $\Delta D^2H$ as the growth during one year, as shown by the equation below.

$$\Delta D^2H = D^2H_{2006} - D^2H_{2005}$$

Moreover, individuals with $D^2H$ smaller than $10^{-4}$ $m^3$ (e.g., $D$ = 0.01 m and $H$ = 1 m) were excluded from the analysis of relationship between tree size or growth rate and environmental factors, due to suppression by adjacent large individuals. The number of planted trees used in our analysis was 7 to 22 in subplots 0–5, 21 to 47 trees in subplots 6–9 and 11 or less in subplots 10–14. *Casuarina obesa* was the dominant species of the eight planted (Table 1), with 87 trees distributed throughout the subplots. There were 66 *Eucalyptus sargentii*, and about 30 *E. leucoxylon, E. occidentalis* and *E. torquata* each (Table 1).

Environmental factors were measured as follows. Ground level was measured along the center line of the plot from the western to the eastern edge. The western edge was assigned as the data point for 0 m in height. Electrical conductivity ($EC_{1:5}$) of the soil 0.3–0.4 m deep was determined without replication every 10 m along the central line of the plot. Soil samples obtained by cylindrical samplers with 0.05 m diameter and 0.05 m length were dried to a constant weight, after which about 10 g soil was added to 5 times the weight of water with thorough stirring, and then $EC_{1:5}$ of the supernatant solution was measured after leaving it to settle. Soil water sensors (EC-20, Decagon Devices Inc., WA, USA) were set up horizontally at depths of 0.1, 0.5 and 0.8 m in 4 holes that were dug at 50-m intervals along the northern side of the plot (holes 1–4, Fig. 1). Data loggers (UIZ3635, UIZIN, Tokyo, Japan) connected to the sensors were placed above the ground and data was collected hourly. We monitored soil water content for one and a half years, from March 11, 2006 to September 6, 2007. Voltage output values were converted to volumetric water content rate ($\theta$)

**Table 1. Afforested tree species and their numbers in the research plot**

| Species | $n$ (1.2 $ha^{-1}$) |
|---|---|
| *Eucalyptus sargentii* | 66 |
| *E. leucoxylon* | 30 |
| *E. occidentalis* | 29 |
| *E. torquata* | 27 |
| *E. camaldulensis* | 6 |
| *E. spathulata* | 5 |
| *E. longicornus* | 3 |
| *Casuarina obesa* | 87 |
| Total | 253 |

using the following equation for clay soil:

$$\theta = 0.000359 \times V - 0.28$$

where $\theta$ is the volumetric soil water content (in $m^3$ $m^{-3}$) and $V$ is the voltage output from the soil water sensor (in $V$) (manuals, Decagon Devices and Meiwafosis Co., Ltd., Osaka, Japan). Daily average values were obtained. Saturated water content is about 0.3 $m^3$ $m^{-3}$ (expressed as volumetric soil water content) in the case of clay[9]. We defined waterlogging as $\theta \geq 0.3$. We also determined permeability coefficients of soil sampled from a depth of 0.3 m in holes 1–4 using the constant head permeability method[2].

Daily rainfall was monitored by a Rain Collector II precipitation pulse transmitter (Davis Instruments, CA, USA) with a HOBO H07-002-04 data logger (Onset Computer Corporation, MA, USA) from March 1, 2007 to September 6, 2007. Prior to that time, insufficient data was supplemented with data from the Tammin Meteorological Observatory (S31°64', E117°49', 242 m asl).

We applied the generalized linear model (GLM), which allows the verification of interaction hypotheses and the main effects of the factors, as well as their respective estimates. We tried to determine the relationship, if any, between the sizes and growth rates of the afforestation trees and two environmental factors: salinity and waterlogging. We also clarified any interspecific differences in size or growth rate. We adopted the soil $EC_{1:5}$ value and ground level of each subplot as variables in order to show gradients of environmental factors, which were dependent variables showing a Gaussian distribution. $EC_{1:5}$ is convenient for determining salt concentration in soil. For $EC_{1:5}$ measurement, soil was sampled from lattices at the center line and longer sides of the subplots. It was determined that a close relationship existed between ground level and waterlogging intensity (see Results). We used the ground level at the center of the subplot. Each outcome for dependent variables, which modeled size and growth rate, was assumed to be generated from a Gaussian distribution function, and size and growth rate were linearly combined with the environmental factors. The interaction of waterlogging and salinity was expected to affect the size and growth rate of afforested trees. We established *E. camaldulensis*, which is used globally as an afforestation tree because of its superior acclimation ability and sound growth[17], as the standard for size and growth rate of trees planted in this plot in order to clarify interspecific differences in size and growth. We conducted the above analysis using R, statistical software.

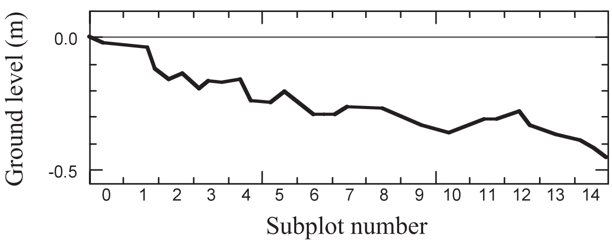


**Fig. 2. Ground level based on the western edge of the research plot**

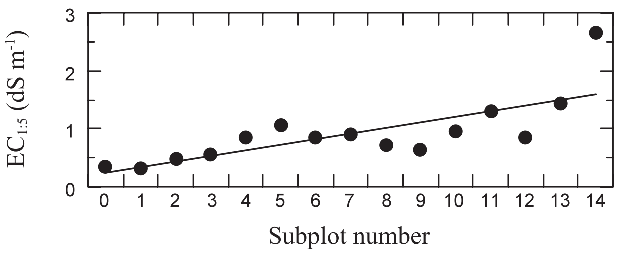


**Fig. 3. Soil EC value at 10-m intervals along the center line**

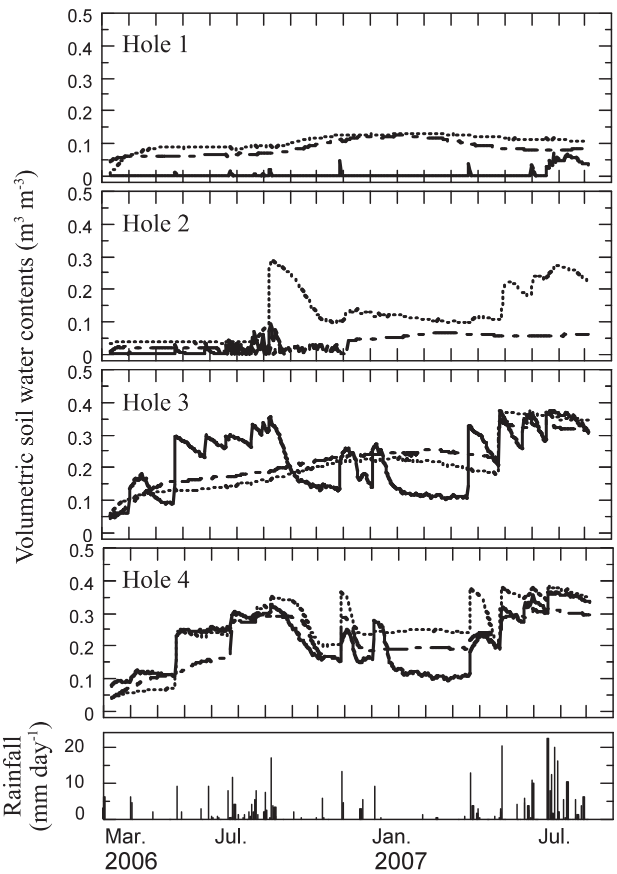


**Fig. 4. Daily changes in volumetric soil water content at depths of 0.1, 0.5 and 0.8 m in holes 1, 2, 3, and 4, and in amount of precipitation**

The sensor 0.1 m deep in hole 2 broke down during the monitoring period.

—— 0.1 m, ········ 0.5 m, — - - 0.8 m.

## Results

The afforestation site has a gradual downward slope. The ground level decreases by 0.48 m for each horizontal distance of 150 m (Fig. 2). The permeability coefficient of soils from the four holes ranged from 2.14 × $10^{-6}$ at hole 4 to 5.04 × $10^{-7}$ m $s^{-1}$ at hole 2. These low values are equivalent to that of silt clay soil, which requires a long time for water to infiltrate. The $EC_{1:5}$ value of soil along the center line was low at the western (0.34 dS $m^{-1}$) and high at the eastern end (2.7 dS $m^{-1}$) (Fig. 3).

The increase in soil water content after rainfall was conspicuous at hole 4, which was located at a lower level, and a high water content was retained for a half month or more at depths of 0.1, 0.5 and 0.8 m (Fig. 4), especially in the rainy season. The change in water content 0.1 m deep in hole 3 showed a similar tendency as the change in hole 4, with high water content following heavy rainfall. The water content 0.5 and 0.8 m deep in hole 3 increased rapidly at the beginning of June 2007, during continuous rainfall, and eventually reached waterlogged conditions. Water content at a depth of 0.1 m in holes 1 and 2 responded immediately to heavy rainfall. Water content at depths of 0.5 m and 0.8 m in hole 1 was stable without waterlogging throughout the monitoring period. There was a tendency toward waterlogging at the lower part of the site, which was retained throughout the rainy season. In contrast, no waterlogging occurred at the higher part of the site. The ground level was considered to be an indicator of waterlogging intensity, including its duration and frequency.

The average individual tree size ($D^2H$) in the 15 subplots varied from 0.0001 to 0.07 $m^3$. Tree size was smaller toward the eastern side (Fig. 5 (a)). Growth rate ($\Delta D^2H$) showed the same tendency toward being small on the eastern side (Fig. 5 (b)).

We determined several relationships between tree traits and environmental factors and interspecific differences by applying a generalized linear model as follows. Tree size was significantly smaller at lower ground levels, where waterlogging was intense (Table 2 (a)). On the other hand, although it was not significant, there was a tendency toward small tree size at places with high $EC_{1:5}$ values ($P$ = 0.11). Both *E. occidentalis* and *E. sargentii* exceeded *E. camaldulensis* in size (Table 2 (a)). Moreover, their growth rate was also affected by waterlogging and was suppressed at a low ground level (Table 2 (b)). There was a tendency toward a smaller growth rate at places with higher $EC_{1:5}$ values ($P$ = 0.084), however it was not significant. The growth rate of *E. occidentalis*, *E. sargentii* and *E. torquata* was larger than that of *E. camaldulensis*. There were slight effects of interactions of waterlogging and $EC_{1:5}$ on tree size ($P$ = 0.13) and growth rate ($P$ = 0.16).

## Discussion

A slight difference in ground level (< 0.5 m) generated a large environmental gradient. For example, although the horizontal position was nearly the same between a 0.1 m depth at hole 4 and a 0.5 m depth at hole 1 or between a 0.5 m depth at hole 4 and a 0.8 m depth at hole 1 (see Fig.

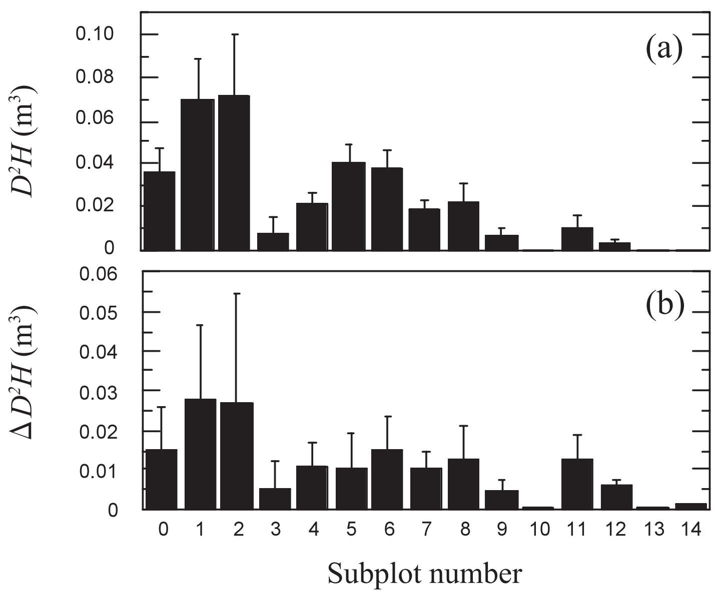


**Fig. 5. Average individual tree size ($D^2H$)(a) and growth rate ($\Delta D^2H$)(b) in each subplot**
Bars show SE.

**Table 2. Relations among sizes of afforestation tree species, environmental factors ($EC_{1:5}$ of soil and ground level) (a), and among growth of afforestation tree species and environmental factors (b), as analyzed by GLM**

(a) Size

| | | *Estimate* | *S.E.* | *t-value* | *P* |
|---|---|---|---|---|---|
| (Intercept) | | 0.0277 | 0.0185 | 1.50 | 0.134 |
| | *E. occidentalis* | 0.0464 | 0.0177 | 2.62 | 0.00948** |
| | *E. sargentii* | 0.0722 | 0.0175 | 4.12 | 5.19E-05*** |
| | *E. torquata* | 0.0331 | 0.0184 | 1.80 | 0.0737. |
| Species | *E. leucoxylon* | 0.0201 | 0.0182 | 1.10 | 0.271 |
| | *E. spathulata* | 0.0348 | 0.0246 | 1.42 | 0.158 |
| | *E. longicornus* | 0.0366 | 0.0294 | 1.24 | 0.215 |
| | *C. obesa* | 0.0194 | 0.0171 | 1.13 | 0.258 |
| $EC_{1:5}$ | | -2.63E-04 | 1.65E-04 | -1.60 | 0.111 |
| Ground level | | 0.00337 | 7.05E-04 | 4.78 | 3.07E-06*** |
| $EC_{1:5}$×Ground level | | -1.22E-05 | 7.99E-06 | -1.52 | 0.129 |

(b) Growth rate

| | | *Estimate* | *S.E.* | *t-value* | *P* |
|---|---|---|---|---|---|
| (Intercept) | | 0.00944 | 0.00818 | 1.16 | 0.249 |
| | *E. occidentalis* | 0.0205 | 0.00786 | 2.61 | 0.00974** |
| | *E. sargentii* | 0.0360 | 0.00777 | 4.63 | 5.95E-06*** |
| | *E. torquata* | 0.0162 | 0.00816 | 1.99 | 0.0480* |
| Species | *E. leucoxylon* | 0.0136 | 0.00807 | 1.69 | 0.0923. |
| | *E. spathulata* | 0.0159 | 0.01089 | 1.46 | 0.146 |
| | *E. longicornus* | 0.0180 | 0.01303 | 1.38 | 0.168 |
| | *C. obesa* | 0.0098 | 0.00760 | 1.29 | 0.199 |
| $EC_{1:5}$ | | -1.27E-04 | 7.31E-05 | -1.74 | 0.0838. |
| Ground level | | 0.00122 | 3.13E-04 | 3.92 | 1.17E-04*** |
| $EC_{1:5}$×Ground level | | -4.94E-06 | 3.54E-06 | -1.40 | 0.164 |

Species were compared with *E. camaludulensis.*
'***', '**', '*', and '.' are significant at the levels of $P < 0.001$, $P < 0.01$, $P < 0.05$, and $P < 0.1$, respectively.

2), seasonal changes in soil water content differed (Fig. 4). When waterlogging occurred in hole 4, no waterlogging occurred in hole 1. The change in water content due to heavy rainfall at the higher part of the site was slight and instantaneous, whereas the change at the lower part was retained for the entire rainy season. One of the reasons for this is likely to be low soil water permeability. The salt level of the soil rose gradually from the western to the eastern edge. The effect of salt on the trees was slight in this abandoned field. On the other hand, there was an obvious effect from waterlogging on the size and growth of afforested trees. Trees under waterlogged conditions tended to be small with a slow growth rate.

The salt classification system[12] in Australia defines four levels: slight, moderate, high, and extreme, based on the salinity of soil, with the respective range of $EC_{1:5}$ values for soil salinity of 0.17–0.5, 0.5–1, 1–2, and > 2 dS $m^{-1}$. The original criterion used units of ECe, which we converted to $EC_{1:5}$ by a correlation equation[10]. The salinity level ($EC_{1:5}$) ranged from slight to moderate in subplots 0–10 (excluding subplot 5), high in subplots 5, 11 and 13, and extreme in subplot 14. The salinity effect was slight on most afforestation trees, which were somewhat tolerant to salt. *Eucalyptus camaldulensis* had moderate salt tolerance[12], *E. occidentalis* and *E. sargentii* had high tolerance[12], and *C. obesa* had extreme salt tolerance[12]. Marcar and Crawford[12] described *E. occidentalis*, *E. camaldulensis*, *E. leucoxylon*, *E. sargentii*, *E. spathulata*, and *C. obesa* as species that were at least moderately tolerant to waterlogging. Our results clarified the degree of impact of salt level and waterlogging on tree size and growth rate. Waterlogging causes heavier damage compared to salinity. *Eucalyptus camaldulensis* has many advantages as a worldwide afforestation tree species with fast growth and superior acclimation ability to various habitats[17]. However, in locations most affected by waterlogging, *E. occidentalis* and *E. sargentii* would be more suitable for planting (Table 2), because they will grow larger than *E. camaldulensis*.

According to our study results, it would be difficult to plant and grow trees at an abandoned waterlogged site. The trees would suffer from waterlogging during the rainy season and could not be expected to control soil water through transpiration. Trees should be planted at the higher part of the site where waterlogging does not occur. Sound growth would lead to considerable transpiration, which would reduce the soil water content and gradually reduce the area suffering from waterlogging[13,14]. It is essential for the rehabilitation of abandoned fields to generate positive feedback between tree growth and prevention of waterlogging, enabling sustainable usage of agricultural land[13]. An effective method of afforestation is likely to rely on planting fast-growing species, such as *E. camaldulensis*, at relatively high ground, and stress-tolerant species, such as *E. occidentalis* and *E. sargentii*, at relatively low ground, with *C. obesa* planted where conditions would be too severe for most other plants. Moreover, we recommend a method where planting is started at a relatively high ground level and gradually extends to sites at a lower level, with monitoring of the water table level and salt concentration.

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