Temporal changes in soil water contents of forests dominated by *Casuarina equisetifolia* on Nishijima Island before and after their eradication

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Abstract: An invasive woody species, *Casuarina equisetifolia* Forst. (Casuarinaceae), is strongly dominant in the forests it invades in the Ogasawara Islands. For the restoration and management of these forest ecosystems, eradication and control programs aimed at *C. equisetifolia* are ongoing on the islands. The eradication can affect the water balance by altering hydrological processes, such as evapotranspiration, throughfall, stemflow, and rainfall canopy interception. In this study, we showed temporal changes in the water contents of surface soils in forests dominated by *C. equisetifolia* on Nishijima Island before and after their eradication. Volumetric water contents of surface soils at sites where all trees of *C. equisetifolia* were killed by herbicide and those of adjacent control sites were measured. The measurements of the soil water contents have been conducted from July 10, 2012 to August 31, 2013 at hourly interval. After August 2012, the soil water contents in the removal quadrats have trended to be higher than those in the control quadrats. The increases in soil water contents just after the removal treatment suggested that death of *C. equisetifolia* by the treatment would result in increase in soil water content. The complete data set of soil water contents in this study is available in electronic format with the permission of the Ogasawara Research Committee of Tokyo Metropolitan University (island@tmu.ac.jp).

Keywords: exotic plants, invasive trees, manipulative removal experiment, Ogasawara Islands, subtropical oceanic island, volumetric water content of soil

Introduction

Casuarina equisetifolia Forst. (Casuarinaceae) is an invasive woody species, native to Malaysia, southern Asia, Australia, and Oceania (Weber 2003), and it has been introduced to many forests in the Ogasawara Islands. It is strongly dominant in the forests it invades and accumulates large amounts of litter under its dense canopy (Hata et al. 2009). This accumulation prevents the initial establishment of native trees (Hata et al. 2010) and alters litter decomposition and litter nitrogen release rates (Hata et al. 2012). For the restoration and management of these forest ecosystems, eradication and control programs aimed at *C. equisetifolia* are ongoing on the Ogasawara Islands (Government of Japan 2010). However, predicting whether ecosystem functions will be appropriately restored is difficult since information regarding the efficacy of the programs is lacking.

Eradicating *C. equisetifolia* would result in the loss of large amounts of biomass from the forests, which would alter the forest water balance via changes in water inputs and outputs. For example, the death of large trees, representing large amounts of biomass, often caused reductions in ecosystem water outputs through losses in transpiration (e.g., Bren et al. 2010; Hawthorne et al. 2013). Furthermore, the eradication of *C. equisetifolia* would cause exposed canopies and reductions in water interception by litter, both of which may increase water inputs. Conversely, canopy exposure and loss of litter may alter water output by enhancing evaporation from the soil surface.

In this study, we showed temporal changes in the water contents of surface soils in forests dominated by *C. equisetifolia* before and after their eradication.

Study sites and methods

Study sites

This study was conducted in forests dominated by *C. equisetifolia* on the island of Nishijima (27°07’10’’N, 142°10’00’’E; area = 49 ha; highest altitude = 100 m). In the 2000s, secondary forests dominated by *C. equisetifolia* were the major vegetation type on Nishijima, while the remaining area was covered by the perennial grass *Zoysia tenuifolia*, a type of secondary vegetation suppressed by feral goat grazing (Abe 2007). Furthermore, invasive black rats (*Rattus rattus*; density ca. 90 individuals ha^{-1} in 2009; Hashimoto 2009) had damaged various kinds of fruiting vegetation by this time (Abe 2007). Forty-one feral goats were removed in 2002 and 2003, and eradication was confirmed in 2007 (Government of Japan 2010). The eradication allowed for an expansion of forests dominated by *C. equisetifolia* because of releases from grazing and trampling of the goats; they increased from 4.6 to 17.6 ha between 1979 and 2006

(Abe et al. 2011). In addition, black rats were controlled with rodenticides between 2007 and 2010, and their population density consequently decreased (Hashimoto 2009; K. Kawakami, unpublished data), which also may have promoted the expansion of *C. equisetifolia*. A program to eradicate *C. equisetifolia* was implemented in 2010 (Kawakami et al. 2011) and study areas were established to evaluate any effects eradication may have on vegetation recovery processes.

On June 10, 2012, five 10 × 20-m sites were selected in forests in dominated by *C. equisetifolia*. At each site, removal treatment was conducted in a 10 × 10-m area (east side, removal area) and not in another 10 × 10-m area (west side, control area) (Fig. 1). A 1 × 1-m quadrat was established at the center of each area.

The forest structure around quadrats in the removal areas was likely similar to that in control areas before *C. equisetifolia* tree were removed (Table 1). Although there were significant differences in the basal areas of all trees among five sites (nested one-way analysis of variance, ANOVA: $F_{(1, 4)} = 20.45$, $P = 0.006$), significant differences in the basal areas of all trees, including dead *C. equisetifolia* trees, between removal and control areas at each site were not detected (nested one-way ANOVA: $F_{(1, 4)} = 0.40$, $P = 0.56$). Including dead trees, the basal area of *C. equisetifolia* per total basal area ranged from 68.4% to 100%, but no differences were observed in the basal area of *C. equisetifolia* trees between the removal and control areas at each site (nested one-way ANOVA, $F_{(1, 4)} = 3.18$, $P = 0.15$).

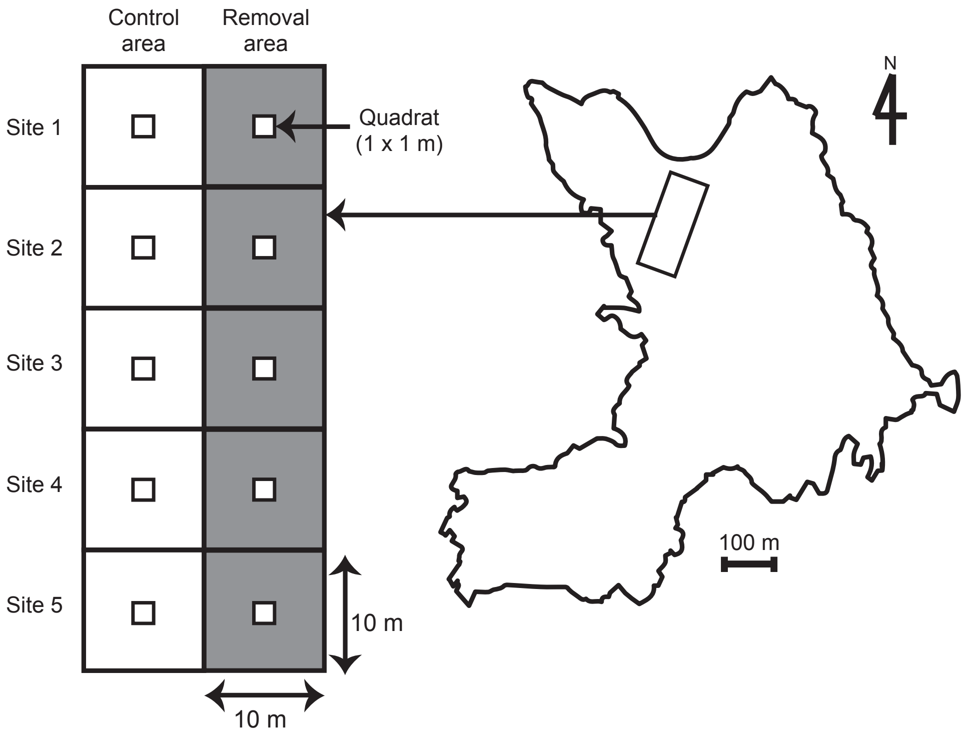

Fig. 1 Distributions of study sites and quadrats on the island.

Table 1 Basal area (m^2 ha^{-1}, BA) of trees greater than 1.3 m in height in a 100-m^2 (10 × 10 m) area around removal and control quadrats at five sites in June 2012.
C, Control quadrat; R, Removal quadrat.

	Site 1		Site 2		Site 3		Site 4		Site 5	
Species	C	R	C	R	C	R	C	R	C	R
Casuarina equisetifolia	32.9	86.7	111.4	86.9	37.3	105.6	124.5	118.8	119.5	128.4
Pandanus boninensis		3.4			17.3		23.2		13.2	
Lagerstroemia subcostata							3.7			
Total	32.9	90.1	111.4	86.9	54.6	105.6	151.4	118.8	132.7	128.4

Removal of *C. equisetifolia*

Removal treatments were conducted on July 5-10, 2012. All *C. equisetifolia* trees present within the removal areas were killed by herbicide. A glyphosate herbicide (Roundup Max Load; Nissan Chemical Industries, Ltd., Tokyo, Japan) was infused into holes 12 mm in diameter and 100 mm in depth created by an electric knife on the tree trunk at 0.2 m above the ground. The appropriate herbicide volumes to kill trees completely were based on logistic regression models that used *C. equisetifolia* diameter at beast height (Fujinuma et al. 2008). We used a minimum of four holes per a tree at equal distances. Additional holes were made when the appropriate amount of herbicide exceeded the capacity of the four holes. Equal volumes of herbicide were infused into each hole.

Measurements of soil water content

The water content of surface soils was measured at the 10 quadrats. Volumetric soil water content at 10 cm below the surface was measured using a theta probe (SM150, Delta-T Devices, Cambridge, UK) with data logger (MJ-12, Environmental Measurement Japan Co. Ltd., Fukuoka, Japan). The theta probe generates a 100-MHz sinusoidal signal and measures the impedance of the sampling volume (Kaleita et al. 2005). The values produced by the probe (voltage, V) were converted to volumetric soil water content, θ_v (m^3 m^{-3}), using the following equation:
$\theta_v = [(1.07 + 6.4V - 6.4V^2 + 4.7V^3) - 1.3]/7.7$ (Delta-T Devices 1999)
The measurements of soil water contents have been conducted from July 10, 2012 to August 31, 2013 at hourly interval. A control quadrat at one site (Site 2) and a removal quadrat at one removal site (Site 5) could not be measure after February 6, 2013 and December 3, 2012, respectively because of technical troubles of the sensor and logger.

Measurements of canopy openness and litter accumulation

Total canopy openness was measured based on hemispherical photographs to estimate light exposure in the removal area. In each quadrat, a hemispherical photograph was taken at noon on July 11, October 6, 2012, and February 7, 2013 (a cloudy day) using a digital camera (Coolpix 880, Nikon, Tokyo, Japan) with a fisheye converter (FC-E9 0.2x, Nikon). Photographs were then analyzed with HemiView 2.1 Canopy Analysis Software (Delta-T Devices) to calculate total canopy openness 0.1 m above the ground. In addition, interval photography has been conducted between July 7, 2012 and July 6, 2013 at 24 hours interval using a digital camera (Recolo, King Jim Co. Ltd., Tokyo, Japan).

To measure amounts of accumulated litter, we collected litter at one randomly chosen 0.2 × 0.2-m location near each quadrat on June 21, 2012, February 7 and July 14, 2013. Litter was dried at 70ºC for 72 h and weighed.

Results and Discussion

There were roughly similar trends in temporal changes in monthly mean values of soil water content and their variances among five sites (Fig. 2). The soil water contents in the removal quadrats drastically increased in August 2012 but not in the control quadrats. After August 2012, the soil water contents in the removal quadrats have trended to be higher than those in the control quadrats. The increases in soil water contents just after the removal treatment suggested that death of *C. equisetifolia* by the treatment would result in increase in soil water content.

Mean values and variances in soil water contents trended to be different among months regardless of the presence of the removal treatments. Those between January and March 2013 trended to be smaller than those in other months. The differences in the variances may be related to amounts of rainfall. Mean values of monthly precipitation between 1969 and 2013 are 70.4 mm in January, 57.9 mm in February and 70.9 mm in March, which are smallest three values (Japan Meteorological Agency, Tokyo, Japan). Lack of rainfall can reduce soil water contents and their variances.

Total canopy openness in the removal areas trended to increase after the removal treatments (Fig. 3a). In July 2012, no significant differences in total canopy openness between removal and control quadrats (nested-ANOVA, $F_{(1, 4)} = 0.04$, $P = 0.86$). On the other hands, quadrats where *C. equisetifolia* had been removed had marginally and significantly higher values of total canopy openness than control quadrats in October 2012 (nested-ANOVA, $F_{(1, 4)} = 4.87$, $P = 0.09$) and February 2013 (nested-ANOVA, $F_{(1, 4)} = 145.95$, $P < 0.001$), respectively. The increases in total canopy openness would be due to exposure of forest canopies by death *C. equisetifolia* and subsequent defoliation. It is consistent with results of the interval photography that leaves of *C.*

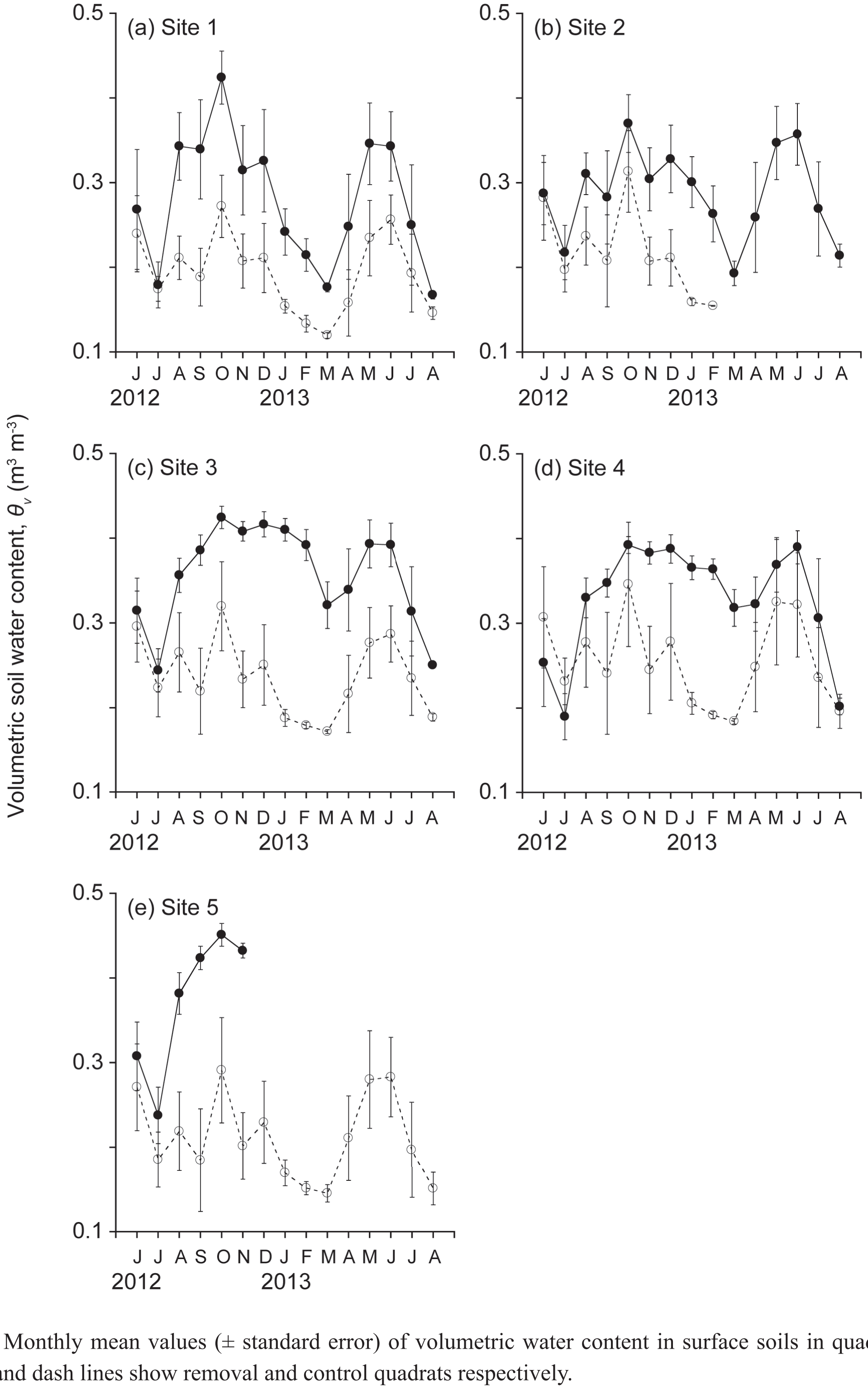

Fig. 2 Monthly mean values (± standard error) of volumetric water content in surface soils in quadrats. Solid and dash lines show removal and control quadrats respectively.

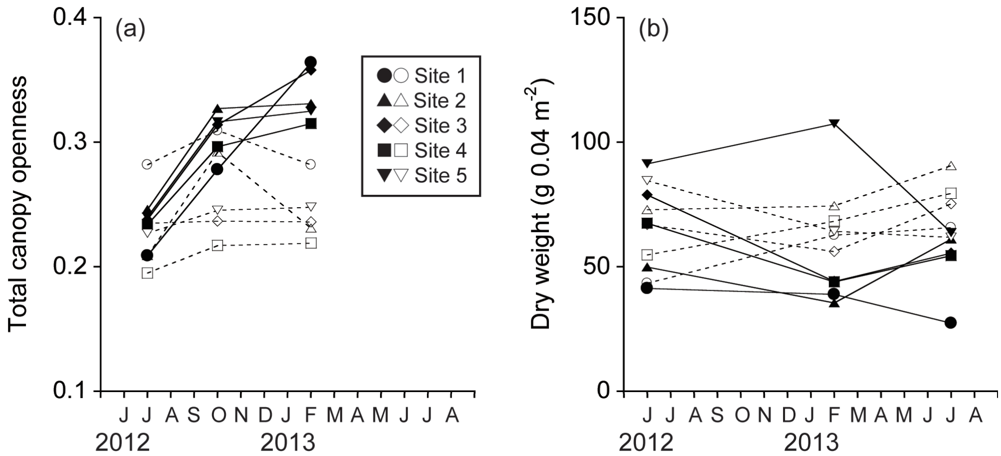

Fig. 3 (a) Total canopy openness and (b) dry weights of accumulated litter near quadrats. Solid and dash lines show removal and control quadrats respectively.

equisetifolia have been defoliated completely after approximately one month of the treatment.

It was observed that most of the accumulated litter was dead leaves of *C. equisetifolia*. Amounts of accumulated litter trended to decrease after the treatment (Fig. 3b). Significant differences in dry weights of accumulated litter between the removal and control quadrats were not detected in June 2012 and February 2013 (nested-ANOVA, $F_{(1, 4)} = 0.04$, $P = 0.86$, $F_{(1, 4)} = 0.62$, $P = 0.48$, respectively). In July 2013, the dry weights in the removal quadrats were significantly higher than those in the removal quadrats (nested-ANOVA, $F_{(1, 4)} = 10.81$, $P = 0.03$). The reduction of the litter in the removal quadrats suggested decomposition of the dead leaves without litterfall after death of *C. equisetifolia* trees.

We demonstrated temporal changes in water contents of surface soils in forests dominated by *C. equisetifolia* before and after their eradication. Data of the soil water contents in this study can be used for further analyses. The complete data set of soil water contents in this study is available in electronic format with the permission of the Ogasawara Research Committee of Tokyo Metropolitan University (island@tmu.ac.jp).

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ABSTRACT IN JAPANESE

西島のトクサバモクマオウが優占する森林における トクサバモクマオウ駆除前後の土壌含水量の時間変化

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在来生態系の保全・復元のために、現在、小笠原諸島では、外来木本種であるトクサバモクマオウの駆除が実施されている。トクサバモクマオウの駆除は、土壌への通過雨量や蒸発散量などの水文学的な過程の変化を介して、土壌水分量を変化させる可能性がある。本研究では、西島において実験的にトクサバモクマオウを駆除した森林の土壌含水量の時間的変化の記録を示す。西島のトクサバモクマオウが優占する森林において、トクサバモクマオウを駆除した場所（以下駆除区）と隣接する駆除していない場所（以下対照区）に、データロガーを接続した土壌水分センサーを設置し、地表 10 ㎝における体積土壌含水率を測定した。この測定は、駆除処理の約 1 か月前から駆除処理の約 1 年後までの間、1 時間おきに実施した。駆除区における土壌含水率は、2012 年 8 月以降、対照区におけるそれより大きくなった。これは、駆除処理に伴う水文学的過程の変化を介して､土壌含水率が増加したことを示唆した。以上の土壌含水率のデータに関しては、首都大学東京小笠原委員会を通して利用することが可能である。利用を希望する場合の問い合わせ先は、以下のアドレス（island@tmu.ac.jp）である。

キーワード： 外来植物、侵略的外来樹木、操作実験、小笠原諸島、亜熱帯島嶼、土壌体積含水率