Effects of Rate and Timing of Fertilizer Application on Yield of Macadamia (*Macadamia integrifolia* Maiden & Betche) in Japan

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Abstract We carried out experiments to determine the optimal rate and timing of fertilizer application to macadamia (*Macadamia integrifolia* Maiden & Betche) in Wakayama Prefecture, Japan. To determine the optimal rates of fertilizer application, fertilizer was applied once a year in a macadamia orchard lying on gray lowland soils after converts in from paddy fields. The fertilizer was applied in April, at a rate of 150, 300 or 450 kg N/ha. The maximum yield was obtained with a fertilizer application rate of 150 kg N/ha/year. The timing of fertilizer application was studied in a macadamia orchard lying on brown earth in the upland soils of Susami, southern Wakayama Prefecture. Fertilizer (300 kg N/ha) was applied in three different ways: total amount applied in spring (April); half-amount applied in spring (April) and half-amount applied in autumn (October); or total amount applied in autumn (October). The highest yield was obtained when the total amount was applied in spring (April).

Key words: Canopy volume, Cumulative yield, Orchard converted from paddy field

Introduction

Macadamia, commonly referred to as the “king of nuts”, is native to Australia. The main producer and exporter countries of macadamia are Australia, the Republic of South Africa (RSA), and the United States (Hawaii). Previously, we demonstrated that it was possible to cultivate macadamia in Wakayama Prefecture, Japan (Maeda *et al.* 2010), but that higher yields are required for commercial cultivation. To this end, it is important to increase flower bearing, the percentage of fruit-set, and fruit size. Yonemoto (2009) reported that insufficient rates of nitrogen fertilizer application resulted in decreased flowering and small, poorly developed inflorescences. Consequently, it is important to determine the optimum rate and timing of fertilizer application to ensure a stable supply of macadamia. However, the appropriate amounts and optimum timing of fertilizer application have not been comprehensively analyzed for this crop. Although there are several reports on the timing of fertilizer application for macadamia grown in Australia and the RSA (Cull, 1984; Manson and Sheard 2007), these standards cannot be applied directly to Japan due to the differences in soil types and climatic conditions.

In general, the soils in fruit orchards in Wakayama Prefecture can be categorized into four different types. Hillside orchards lie on brown earth, new large-scale orchards developed by leveling mountains lie on lithosol, gently sloping hillside orchards lie on yellow soil, and orchards converted from paddy fields lie on gray lowland soil. In the present study, we examined the effects of the application of different amounts of fertilizer on macadamia yield over a 3-year period. The orchard lay on gray soils, and had been converted from paddy fields. In addition, we examined the effects of the timing of fertilizer application on yield of macadamia trees grown on brown earth in the upland soils of Susami, Wakayama Prefecture, over a 3-year period.

Materials and Methods

Scions of two cultivars, ‘Beaumont’ and ‘Keau’, introduced from California and Hawaii, respectively, were grafted onto ‘Kau’ seedlings in 1986. These seedlings had been grown from seeds obtained from Hawaii in
1984.

**Experiment 1: Effect of fertilizer application rate on macadamia nut yield**

‘Beaumont’ scions were planted in bare ground at 5 m intervals with a 5 m distance between trees in an orchard converted from paddy fields in Araigawa, Wakayama Prefecture, in 1988. The experimental field was subdivided into three sections for fertilizer experiments. The fertilizer used was isobutylidene diurea (IB) compound fertilizer (N: P₂O₅; K₂O = 10: 10: 10). Fertilizer was applied to each section at a rate of 150, 300, or 450 kg nitrogen component per hectare annually. Each treatment consisted of six trees and was separated from adjacent subplots by an open row to prevent cross-contamination from different fertilizer regimes. Price (1981) reported that the application rate of fertilizer (N: P₂O₅; K₂O = 13.2: 2.2: 13.3) to adult trees was 6 kg per annum per tree. Conversion of that rate to the planting distance used in the present study resulted in 317 kg of nitrogen component per hectare. Thus, the fertilizer application rates were determined based on a reference of 300 kg per hectare. During the three-year period from 2006 through 2008, all of the fertilizer was applied on April 1 each year, with fertilizer application coinciding with the growth period of macadamia shoots in Wakayama Prefecture.

The canopy volume was measured by the ‘seven-multiplication method’ each year on April 1 (Iba et al., 1987). Cutting back and pruning were performed to allow access, but no further pruning or fruit thinning was carried out. Irrigation was provided as required. Harvest was carried out in mid- and late January every year from 2007 to 2009 and yield was measured as based on the number of pericarps per tree and per canopy volume. ‘Beaumont’ was harvested and analyzed before fruit drop, which begins in February.

Before the application of fertilizer on April 1, 2006, soils were collected from a depth of 10 cm at three sites in the experimental field. The collected soil was mixed, air-dried at room temperature, and sieved through a 2 mm mesh sieve. After the addition of 100 mL 1 N potassium chloride (pH 7.0) to 40 g dry soil, the mixture was shaken for 60 min and then allowed to settle for 30 min before the measurement of the pH with a pH meter (D-54, Horiba, Ltd., Japan). To determine the electrical conductivity (EC), 100 mL of distilled water was added to 20 g dry soil, the mixture was shaken for 60 min, and then EC was determined with an EC meter (D-54, Horiba, Ltd.). Inorganic nitrogen level in the air-dried soil was measured by filtering the supernatant of the mixture used for the EC measurements and subjecting it to steam distillation. Available phosphate level was measured by the addition of 100 mL 0.002 N sulfuric acid to 0.5 g dry soil, shaking of the mixture for 30 minutes, filtering of the supernatant, and determination of the absorbance using a spectrophotometer (V-550, Jasco Co., Japan), according to the Truong method. Exchangeable cation levels were measured by the addition of 100 mL of 1 N ammonium acetate to 5 g dry soil, shaking of the mixture for 60 min, filtering of the supernatant, and then dilution with strontium chloride to a final concentration of 1,000 ppm. Then, the sample was analyzed by atomic absorption spectrophotometry (Solaar AA, Thermo Fisher Scientific Inc., Japan).

**Experiment 2: Effect of timing of fertilizer application on macadamia yield**

‘Keaau’ from Hawaii was planted in bare ground at 5 m intervals with a 5 m distance between trees in an experimental field in Susami, Wakayama Prefecture in 1988. IB compound fertilizer (N: P₂O₅; K₂O = 10: 10: 10) was applied annually at a rate of 300 kg of nitrogen component per hectare. The experimental field was subdivided into three treatments for the timing of fertilizer application experiments. Fertilizer was applied in three different ways: total amount applied in spring (spring treatment); half-amount applied in spring and half-amount in autumn (spring/autumn treatments); and total amount applied in autumn (autumn treatment). As before, each treatment consisted of six trees and was separated from adjacent treatments by an open row to prevent cross-contamination from different fertilizer regimes. All the other aspects of cultivation management were the same as those described in Experiment 1. During the three-year period from 2006 to 2008, fertilizer was applied on April 1 for the spring treatment and on October 1 for the autumn treatment. The timing of fertilizer application was the same as that used in Experiment 1, i.e., at the time of shoot production in macadamia trees in Wakayama Prefecture in April and October. Harvest was carried out in early and mid-October each year, and the yield was determined as described for Experiment 1. ‘Keaau’ was harvested and analyzed before fruit drop, which starts in mid-to late October.

**Results and Discussion**

**Experiment 1: Effect of fertilizer rate on macadamia nut yield**

From the second year onwards, the yield of maca-
Macadamia nuts differed depending on the fertilizer rates (Fig. 1). The three-year cumulative yield was highest in the 150 kg N/ha treatment and lowest in the 450 kg N/ha treatment (Fig. 2). In the macadamia orchard converted from paddy fields in Wakayama Prefecture, the yield increased as the amount of applied fertilizer decreased (within the range of this experiment: 150-450 kg N/ha). No significant differences were observed in yield among the treatments in the first year of cultivation (Fig. 1). However, in the second year, the yield was highest in the 300 kg N/ha treatment, followed by the 150 kg N/ha treatment. In the third year, the yield was highest in the 150 kg N/ha treatment, followed by the 300 kg N/ha treatment. Over the 3-year experimental period, the lowest yield was obtained from the 450 kg N/ha treatment. The yield per canopy volume was similar to the yield per tree (Fig. 1). The cumulative yield per tree was highest in the 150 kg N/ha treatment, followed by the 300 kg N/ha treatment, and then the 450 kg N/ha treatment (Fig. 2). The cumulative yield per canopy volume was similar to the cumulative yield per tree.

Orchard fields converted from paddy fields are usually flat, very fertile, and contain high levels of humus. Trees cultivated in these orchards show high nitrogen absorption rates and grow rapidly (Takatsuji, 2000). Okamuro et al. (2010) examined the fertility of brown earth (soil), lithosol, yellow soil, and gray lowland soil in Wakayama Prefecture and reported that the inorganic nitrogen level was highest in gray lowland soils converted from paddy fields. Table 1 shows the soil chemical properties in the field before the start of the experiment. The soil type contained high levels of inorganic nitrogen (5.47 mg/100 g). The levels of phosphates and cations were also high, relative to the requirements for fruit trees, as set out in the Guidelines on Soil Fertilizer Countermeasures in Wakayama Prefecture (2000). Takatsuji (2000) reported that citrus orchards converted from paddy fields required less fertilizer than those on

![Graph](image1.png)

**Fig. 1** Effect of amount of applied fertilizer on yield per tree of macadamia and yield per canopy volume. Means followed by the same alphabetical letters are not significantly different by Tukey’s test ($p<0.05$, n=6).

![Graph](image2.png)

**Fig. 2** Effect of amount of applied fertilizer on cumulative yield per tree of macadamia and cumulative yield per canopy volume. Means followed by the same alphabetical letters are not significantly different by Tukey’s test ($p<0.05$, n=6).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Chemical properties of soil before the onset of Experiment 1.</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.23</td>
</tr>
<tr>
<td>EC</td>
<td>0.18</td>
</tr>
<tr>
<td>Inorganic nitrogen</td>
<td>5.47</td>
</tr>
<tr>
<td>Available phosphate</td>
<td>195</td>
</tr>
<tr>
<td>Exchangeable cations</td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>615</td>
</tr>
<tr>
<td>MgO</td>
<td>78</td>
</tr>
<tr>
<td>K2O</td>
<td>55</td>
</tr>
</tbody>
</table>

The soil was sampled from the upper 10 cm layer on Apr. 1, 2006.
hillside fields, primarily because of the high concentrations of nitrogen already present in the soil and the high fertilizer efficiency of applied nitrogen. Manson and Sheard (2007) reported that excessive nitrogen fertilizer application during the cultivation of macadamia adversely affected yields. In general, excessive application of nitrogen fertilizer results in increased vegetative growth and decreased flowering and percentage of fruit-set (Kobayashi, 1988). In the present study, a marked increase in the canopy volume was observed in the second year when 450 kg N/ha of nitrogen was applied annually (Fig. 3). New shoot growth occurred during the flowering period of macadamia trees, indicating that the large fertilizer application in April likely promoted new shoot growth and decreased the percentage of fruit-set.

Since the planting distance in Hawaii is 10.7 m² (Storey, 1978), therefore, based on the fertilizer application rate indicated by Price (1981), the amount of nitrogen added via fertilizer is equal to 317 kg of the nitrogen component per hectare. Because Hawaii has a higher annual average temperature and annual rainfall than Japan, it is likely that considerable leaching and denitrification of fertilizer occurred. Consequently, nitrogen application rates in Hawaii need to be higher than those used in this experiment. In macadamia orchards converted from paddy fields in Japan, the highest yield was obtained using 150 kg N/ha. The results of the present study indicated that this nitrogen rate should be adopted as the standard for macadamia cultivation in fertile orchards (e.g. converted rice paddies) with high levels of humus in regions with climatic conditions similar to that in Japan.

**Experiment 2: Effect of timing of fertilizer application on macadamia yield**

Among the three timing treatments of fertilizer application, macadamia yield decreased in the following order: spring, spring and autumn, and then autumn (Figs. 4, 5). For macadamia trees cultivated in Wakayama Prefecture, the highest yield was obtained when the total amount of fertilizer (300 kg N/ha) was applied in spring. No significant differences in the yield per tree were observed among the fertilizer application treatments in the first year of cultivation (Fig. 4). However, in the second and third years, the highest yield was obtained in the
spring application treatment, followed by the spring and autumn ones, and then autumn one. In the second and third years, the yield per canopy volume and the yield per tree showed similar trends; that is, highest in the spring fertilizer application treatment, followed by the spring and autumn treatments, and the autumn treatment. The spring fertilizer application treatment showed the highest cumulative yield (12.3 kg per tree). The cumulative yields in the spring/autumn treatments and the autumn treatment were 5.5 and 4.1 kg, respectively (Fig. 5). The trend in the cumulative yield per canopy volume was similar to that of the cumulative yield per tree. The highest cumulative yield per canopy volume was recorded in the spring treatment (611 g), followed by the spring/autumn treatments and then the autumn treatment (Fig. 5). The reason for the lower yield in the autumn treatment is unclear. In Japan, temperatures decrease after October. Therefore, we anticipated that the application of fertilizer in autumn would be ineffective as the fertilizer would not be absorbed, resulting in the decrease of the yield of the autumn-fertilized crop. In addition, much of the fertilizer added in autumn would be lost in runoff in the following spring, resulting in the decrease of fertilizer efficiency. To address these problems, further studies should be carried out in the future.

For temperate fruit trees, spring and autumn fertilizer applications are considered to be important. Takatsuji (2000) reported that fertilizer application to citrus trees in autumn increased the storage of carbohydrates, which are utilized for initial growth during sprouting in the following year. Application of fertilizer in spring enhances the development of spring shoots and young fruit. Since flower budding and flowering of citrus trees occur after the application of fertilizer in spring, the number of flower-bearing stems depends on the air temperature after fertilizer application (Kadoya, 2000). However, in the macadamia trees in Wakayama Prefecture, flower budding occurred at the beginning of January and flower bloom in May (Yonemoto, 1994). Unlike in temperate fruit trees, such as citrus trees, in macadamia trees, flower budding had already occurred in May, and the number of flowers had already been determined at the time of fertilizer application in spring (April). In the RSA and Australia, staggering or splitting of the fertilizer application into five equal amounts is recommended for trees aged 1-3 years. In Australia, a split application of 1/2 of the total annual fertilizer in February, 1/4 in April, and 1/4 in October was recommended for adult trees (Cull, 1984). In the RSA, it was recommended that fertil-izer should be applied in three equal amounts in March, August, and October/November (Manson and Sheard, 2007).

The results show that for macadamia trees cultivated in orchards converted from paddy fields with highly fertile gray lowland soils in Wakayama Prefecture, the highest yield was obtained with a fertilizer application rate of 150 kg N/ha/year. When we examined the timing of fertilizer application to trees growing on brown earth in the upland soils of Susami, southern Wakayama Prefecture, the highest yield was obtained by the application of the total annual amount of fertilizer in spring (April).

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