Improvement of crop yield, soil moisture distribution and water use efficiency in sandy soils by clay application

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Abstract

Cultivating sandy soil is a promising solution to overcome the fight against hunger especially in the developing countries. The main problems of sandy soil are water and nutrients deficiency. A containers experiment was carried out to study the enhancement of water productivity and crop yield of sandy soils treated with clay. The container size was 31×15×60 cm with one transparent side for visual viewing of the root development beside growth characteristics. The soil with bulk density of 1.5 g/cm³ mixed with CaCO₃ and P₂O₅ fertilizers was packed in the containers to 50 cm height. Three treatments: control, overlay and incorporation with four replicates were studied. The control treatment was only sandy soil, 4% by weight of clay was overlaid on the surface of sandy soil to constitute the overlay treatment (5.6 kg soil with 21.4% clay overlay on 28.4 kg sandy soil with 93% sand) while the same percentage of clay was incorporated with the upper 20 cm of sandy soil to represent the incorporation treatment. All the treatments received the same amount of irrigation water and fertilizers during the growing stage.

The results indicate that the leaf area in cucumber and stem length, stem diameter and number of leaves in maize were increased in the treatments treated with clay. About 2.5 times of yield was obtained from those treatments compared to control. Roots grew intensively in the layers treated with clay. The incorporation treatment retained higher amount of water compared to control but with small differences compared to overlay treatment. The water use efficiency and water saving is highly increased by clay application and about 45%–64% of irrigation water can be saved compared with control.

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Keywords: Sandy soil; Clay amendment; Cucumber; Maize; Water use efficiency

1. Introduction

Irrigation water is gradually becoming scarce not only in arid and semi-arid regions but also in the regions where rainfall is abundant. Therefore, the water saving and conservation is essential to support agricultural activities, which account for 85% of the total water consumed. On the other hand, sandy soils suffer due to water deficiency, while intensifying mineral fertilization with irrigation water supply endangers the environment. Therefore, there is need to cultivate the sandy soils to fight against hunger in the world but with the least amount of irrigation water and mineral fertilizers. Treating sandy soil with clay is one of the good options to increase water and productivity with the least use of mineral fertilizers. Water repellency of sandy soil can be reduced by adding small increments of clay content, (Harper and Gilkes, 1994). Reuter (1994) reported that clay-substrate application in sandy soil significantly

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improved soil water regime, especially on the percolation processes. Important consequences of clay addition are reduction of plant nutrient losses and ground water contamination. Addition of clay to the top of sandy soil has been shown to be highly effective in reducing water repellency and increasing crop yield (Obst, 1989; Carter et al., 1998). The most predictive factor which has the greatest effectiveness of clay soil materials in reducing water repellency in sandy soil was texture (McKissock et al., 2000, 2002). Al-Omran et al. (2005) reported that the sandy soil treated with clay deposits increased the crop yield of squash (*Cucurbita pepo*) by 12.8% compared with control treatment. The present study aimed to investigate soil moisture distribution, yield improvement, and water use efficiency of cucumber and maize in sandy soil treated with clay and also to figure out whether overlay the clay on top of soil surface or incorporation it with the surface layer is better.

### 2. Materials and methods

Containers experiment was carried out in a greenhouse situated at JIRCAS Okinawa Subtropical Station, Ishigaki, Japan. The container size was 31 × 15 × 60 cm with one transparent side for visual viewing of the root development beside growth characteristics. The soil with bulk density of 1.5 g/cm³ mixed with CaCO₃ and P₂O₅ fertilizers was packed in the containers to 50 cm height. Three treatments: control, overlay and incorporation with four replicates were studied. The control treatment was only sandy soil, 4% by weight of clay was overlaid on the surface of sandy soil to constitute the overlay treatment (5.6 kg soil with 21.4% clay overlay on 28.4 kg sandy soil with 92.2% sand) while the same percentage of clay was incorporated with the upper 20 cm of sandy soil to represent the incorporation treatment. Two different sandy soils textured, one grown with cucumber (*var. Shin toki wa*) and the other grown by maize (*var. Gold dent KD 777*) were investigated under each treatment (Table 1). At the start of the experiment the containers were saturated with water while they were irrigated manually every 2–3 days during the growth period by adding equal amount of water for all treatments. The plants were fertilized with a Nutricoat fertilizer containing 14% N, 12% P₂O₅ and 14% K₂O. A dosage of 10 g fertilizer was added twice on soil surface during the growing season. Growth characteristics include leaf growth, chlorophyll content in cucumber and stem diameter and length, number of leaves and chlorophyll content in maize were measured. The chlorophyll content measured in leaf number five from the top of the plant in cucumber and in the last complete upper leaf in maize. Cucumber yield for each plant was harvested and recorded twice a week. Soil water content was measured in all treatments during the growing season by Profile Probe method. At the end of the experiment the weight of the aboveground biomass for both cultivars were recorded after dried at 70 °C. The development of roots was observed from the transparent side of the containers during the growing season. At the end of the growing season the roots for each 10 cm depth were collected separately and washed and weighted after dried at 70 °C to study the roots mass over depth for each soil type.

### 3. Results

#### 3.1. Growth characteristics

The growth characteristics of cucumber and maize are presented in Figs. 1 and 2. The results revealed that there were large differences in leaf area, higher in

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Soil 1 (source of clay)</th>
<th>Cucumber soil</th>
<th>Maize soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size analysis</td>
<td>Clay %</td>
<td>21.4</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Silt %</td>
<td>9.2</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>Coarse sand %</td>
<td>48.7</td>
<td>87.6</td>
</tr>
<tr>
<td></td>
<td>Fine sand %</td>
<td>20.7</td>
<td>4.6</td>
</tr>
<tr>
<td>Texture grade</td>
<td>Sandy clay loam</td>
<td>Sand</td>
<td>Sand</td>
</tr>
<tr>
<td>Saturation cm³/cm³</td>
<td>0.45</td>
<td>0.36</td>
<td>0.35</td>
</tr>
<tr>
<td>Sat. hyd. Cond. cm/h</td>
<td>0.54</td>
<td>6.8</td>
<td>8.64</td>
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</table>

Fig. 1. Leaf area index and chlorophyll content in cucumber.
overlay and incorporation treatments than control in cucumber (Fig. 1). The leaf area in overlay and incorporation treatments was similar in the beginning but increased slightly in incorporation treatment from the mid to the end of growing season compared to overlay treatment. Chlorophyll content was the highest in control treatment while there were no differences between overlay and incorporation treatments.

There were no differences in growth characteristics of maize between overlay and incorporation treatments (Fig. 2). The stem length and diameter, number of leaves per plant and chlorophyll content were similar for both treatments. The lowest stem length, stem diameter and number of leaves were found in control treatment. Chlorophyll content was similar up to the mid of the growing season in all the treatments. Thereafter, chlorophyll content increased at a constant rate in control treatment while it decreased followed by an increase with the same rate in overlay and incorporation treatments.

3.2. Shoot and root dry weights

The results of shoot and root dry weights and root–shoot ratio in cucumber indicated that the highest shoot dry weight was obtained in incorporation followed by overlay and control treatments (Fig. 3). The highest shoot dry weight in maize was obtained in overlay while the least obtained in control treatment (Fig. 3A). Root dry weight was recorded the least in control treatment for both cultivars while no differences were found in root dry weight in overlay and incorporation treatments either in cucumber or maize (Fig. 3B). The highest root–shoot ratio in cucumber was obtained in control treatment followed by overlay and incorporation treatments (Fig. 3C). On the contrary, in maize the highest root–shoot ratio was found in incorporation followed by overlay and control treatments.

Fig. 4 shows the dry weight distribution of roots in 0–50 cm soil depth in cucumber and maize. About 60% to 75% of the dry weight was present in 0–10 cm layer in both crops. In this layer, roots dry weight was recorded the highest in overlay followed by incorporation and control treatments. In 10–20 cm depth, the root dry weight in cucumber was the highest in incorporation treatment while the least in overlay treatment. The cucumber root dry weight in 40–50 cm depth was highest in control treatment. The maize root dry weight of incorporation and overlay treatments at 10–20 cm depth was similar but higher than that in control. In maize, the highest maize root dry weight in 20–30 cm depth was recorded in incorporation treatment, while no differences were found between treatments in 30–40 and 40–50 cm depth.

3.3. Yield

The results of cucumber yield presented in Fig. 5 indicated that there were large differences between control and the other treatments. The overlay or incorporation treatments produced 2.5 times higher yield than the control. The overlay treatment produced 793 g/plant, incorporation treatment 786 g/plant and control treatment produced 312 g/plant. Because of poor
pollination in maize, the plants failed to produce grains therefore, the evaluation of the yield was made on the basis of dry matter production. The highest dry matter was produced in overlay followed by incorporation and control treatments (Fig. 3A).

3.4. Soil moisture distribution

Soil moisture distribution during the growing season at 5, 25 and 45 cm depth for cucumber and maize is shown in Fig. 6. The highest soil water content was measured where the highest clay content existed. At 5 cm soil depth, the highest soil water content was obtained in overlay followed by incorporation and control treatments. At 25 cm depth, the highest soil water content was obtained in incorporation while small differences were found between overlay and control treatments. At 45 cm depth, the soil water content in control treatment was the highest except in the last month in maize when it was recorded the lowest. A large variation in soil moisture distribution was found in maize in the last month of the experiment. The results also indicated that increasing soil depth under both crops increased the soil water content in the control treatment.

The change in soil water content variation before and after 2 h of irrigation event is presented in Fig. 7. At 5 cm depth, the variation was the largest in overlay followed by incorporation and control treatments. At 25 cm soil depth, the highest soil water content was recorded in incorporation followed by control and overlay treatments. No change in soil water content occurred at 45 cm soil depth in all the treatments. The water retained in soil profile (50 cm depth) after 2 h of irrigation was the highest in both crops obtained in incorporation followed by overlay and control treatments (Fig. 8). The least amount of retained water was obtained in maize control treatment.

3.5. Water use efficiency

The amount of water used to produce 1 kg of dry matter in maize or 1 kg of cucumber yield under the
condition of this experiment is shown in Table 2. The lower the amount of water used to produce 1 kg, the higher the water use efficiency. Water use efficiency was the highest in overlay and the least in control treatments in maize while in cucumber the water use efficiency in overlay and incorporation was identical and very low in control. The applications of overlay or incorporation clay on or with sandy soil dramatically increased water saving in both crops. About 45% in maize and 60% in cucumber of irrigation water can be saved compared to control treatment.

4. Discussions

4.1. Growth characteristics

The results of leaf area index in cucumber (Fig. 1) and stem length, stem diameter and number of leaves in maize (Fig. 2) revealed that the control treatment was very low compared to overlay and incorporation treatments. No significant differences were found between overlay and incorporation treatments for both cultivars. The results are due to available soil moisture content especially in cucumber, increase in available soil moisture increased the leaf growth and consequentially leaf area index. In a study on the dynamic analysis of water relations and leaf area in cucumber carried out by Kitano and Eguchi (1993) found that water deficit decreases leaf growth. Around the fair midday, the larger impact of the evaporative demand was imposed on plant water balance, and the competitive relationship between
the higher evaporative demand and transpiration induced the midday water deficit, in which 10% of the shoot water content was lost. This water loss resulted in midday stomatal closure and depression in leaf expansion, which were attributed to decrease in bulk leaf water potential, and turgor. These responses were estimated to related to effects of midday water deficit on diurnal variations in plant hydraulic conductance and leaf extensibility. Also in maize the stem length, stem diameter and number of leaves were the least at control treatment because of the less water content compared to the other treatments. The development of water stress led to reduce the shoot development and leaf extension (Renquist et al., 1982; Roberts et al., 1990; Hoffmann and Turner, 1993). Moreover, restricted water uptake results in low leaf water potential and cessation of leaf and shoot expansive growth (Raviv and Blom, 2001). The chlorophyll content in control treatment in cucumber was the highest compared to the other treatments because the photosynthesis and stomatal conductance were less effected by low soil water content (Roberts et al., 1990) while the number of leaves in control is less than in the other treatments resulting in more chlorophyll content concentration compared to overlay and incorporation treatments (Fig. 1). The decline of chlorophyll content especially in maize for overlay and incorporation treatments at the midseason may be due to the nutrient deficiency. Due to the large vegetative growth of both treatments and insufficient available nutrients in the soil the chlorophyll content is dramatically decreased compared to control, but after supply the second dosage of the fertilizers the chlorophyll content recovered and increased than control treatment (Fig. 2).

4.2. Shoot, root dry weights and root–shoot ratio

The results of shoot dry weight revealed that overlay and incorporation treatments look similar either in cucumber or maize while the least shoot dry weight obtained from control in both cultivars (Fig. 3A). The results were due to the low soil water content for control

![Figure 7: Soil water contented distribution over depth before irrigation (A), after 2 h of irrigation (B) and the change in soil water content (C).](image)

![Figure 8: Retained water after 2 h of irrigation event in maize and cucumber soils.](image)
The gradual decrease in root–shoot ratio from control to incorporation treatment in cucumber (Fig. 3C) could be also due to soil water content. High soil moisture content at the containers bottom of control (Fig. 6) encourage cucumber to develop its root system at 40–50 cm depth resulted in higher root dry weight (Fig. 4) because of the availability of water and nutrients in these layers, but the clay content concentrated at 10 cm depth especially in cucumber. Increase clay content resulted in high root dry weight. Root growth extends in all directions and if it encounters an area high in moisture or minerals it grows and branches profusely because of the less resistance in the wet soil (Kramer, 1995; Al-Omran et al., 2005). After 20 cm soil depth there were no differences in root dry weight between cucumber treatments except for control at 40–50 cm depth where high root dry weight was obtained. The increase in root dry weight in control at that layer was due to the high soil water content at 40–50 cm depth (Fig. 6). The increase in root dry weight at 20–30 cm depth in maize may be due to the increase in clay content transported with irrigation water and precipitated at that depth. Very low root dry weight was found at 40–50 cm depth especially at maize indicating that the root stay where the water and nutrients are available. Similar results reported by Panda et al. (2004) who published that the proper root depth to be considered for scheduling irrigation in maize is 0–45 cm.

### 4.3. Yield

Overlaying or incorporating clay soil with sandy soil resulted in dramatic increase in cucumber yield (Fig. 5) or shoot dry weight in maize (Fig. 3A) compared to control. The ability of clay content to hold water and nutrients is very high compared to sandy soil. Overlaying or incorporating clay soil with sandy soil increased the available water and nutrients at the upper 20 cm soil depth results in the large increase in

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Average water (L) produce 1 kg dry matter</th>
<th>Average water (L) produce 1 kg cucumber yield</th>
<th>Water saving relative to control treatment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>70.7±23.2</td>
<td>17.0±7.6</td>
<td>–</td>
</tr>
<tr>
<td>Cucumber</td>
<td>36.3±2.8</td>
<td>6.1±1.2</td>
<td>49</td>
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<tr>
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</tr>
<tr>
<td>Cucumber</td>
<td></td>
<td></td>
<td>64</td>
</tr>
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</table>

(Fig. 8) because low soil water content reduced shoot and leaf dry weights (Singandhupe et al., 2003). An inadequate amount of available water in soil hampers various physiological processes in plant and finally the crop yield. The high soil water content in incorporation treatment of cucumber (Fig. 8) resulted in the slight increase in shoot dry weight. The condition of limited available water in the soil to support plant growth is the most common form of stress that plants face. Low retained water in control treatment compared to overlay and incorporation treatments for both cultivars reduced root system size of control resulting in low root dry weight (Fig. 3B) because decreasing soil water content reduced root dry weight (Levin et al., 1979). Another reason for the increase in root dry weight in overlay and incorporation treatments for both cultivars compared to control is the presence of clay content. Increase clay content in sandy soil encourages root proliferation intensively, resulting in large root system and consequently high root dry weight. Similar results were published by Al-Omran et al. (2005).

The presence of clay content in sandy soil encourages the maize root to grow intensively especially at the upper 20 cm compared to control. Growing the root rapidly should be met by rapid shoot growth because there is a close correlation between roots and shoot development. The maintenance of a proper balance between them is of great importance. If either is too limited or too great in extent, the other will not thrive. Due to the clay treatment large root and shoot biomass were obtained from overlay and incorporation treatments and resulted in increase in root shoot ration compared with the control (Fig. 3C). Similar results reported by Kang et al. (2002) who said that encouraging the maize root development in soil vertical profile by alternate watering led to an increase in root–shoot ratio.

The largest root biomass was presented in the upper 10 cm of soil depth for all treatments for both cultivars (Fig. 4) because of the availability of water and nutrients in this layer. The highest root dry weight obtained from overlay treatment while the incorporation treatment was in second order because of the high clay content presented in these layers, but the clay content concentrated at 10 cm depth in overlay treatment while distributed in 20 cm depth in incorporation treatment. Distributing clay content at 20 cm depth in incorporation treatment also resulted in an increase in root dry weight at 10–20 cm depth especially in cucumber. Increase clay content resulted in high root dry weight. Root growth extends in all directions and if it encounters an area high in moisture or minerals it grows and branches profusely because of the less resistance in the wet soil (Kramer, 1995; Al-Omran et al., 2005). After 20 cm soil depth there were no differences in root dry weight between cucumber treatments except for control at 40–50 cm depth where high root dry weight was obtained. The increase in root dry weight in control at that layer was due to the high soil water content at 40–50 cm depth (Fig. 6). The increase in root dry weight at 20–30 cm depth in maize may be due to the increase in clay content transported with irrigation water and precipitated at that depth. Very low root dry weight was found at 40–50 cm depth especially at maize indicating that the root stay where the water and nutrients are available. Similar results reported by Panda et al. (2004) who published that the proper root depth to be considered for scheduling irrigation in maize is 0–45 cm.
cucumber yield or maize dry matter. Similar results were found by Tan et al. (1983) and Al-Omran et al. (2005). Slight increase in crop yield for overlay treatment was found compared to the incorporation treatment for both cultivars. The results may be due to the high soil water content presented in the surface layer of overlay treatment. When water content is decreased crop transpiration rate decreased as well resulting in increased crop canopy temperatures and crop water stress indeed values and resulted in reduced yield, (Simsek et al., 2005).

4.4. Soil moisture distribution

The results of soil moisture distribution over depth (Fig. 6), the change in water content after irrigation (Fig. 7) and the retained water (Fig. 8) revealed that higher soil water content is related to the presence clay content. In the overlay treatment which has the high percentage of clay content at the upper 10 cm has the highest soil moisture content because clay minerals presented in the used soil have higher ability for water holding capacity. The addition of clay to sandy soil as a conditioner improved its hydraulic properties by limiting percolation losses while maintaining adequate infiltration rate and water retention (Al-Darby, 1996). As the percolation losses are decreased the retained water is increased, the nutrients losses are decreased consequently soil fertility is increased (Reuter, 1994). The improvement in soil water regime and soil fertility depends on the dominant type of clay minerals (McKissock et al., 2002). Another reason for increasing soil water content in sandy soil overlaid with clay content is the evaporation because the clay amendment decrease the evaporation rate leads to increase in retained soil water (Zayani et al., 1996). The high soil water content measured at 25 cm depth in the incorporation treatment is due to the transported fine clay particles moved with irrigation water and precipitated at the small pore space between sandy soil particles. Precipitation of clay particles in fine pore spaces helps to decrease percolation and increase water retention resulted in higher soil water content. During wetting and drying, some of clay is mobilized. Because of their rough surfaces, some sand grains become quite evenly coated with clay. These changes presumably represent the effect of capillary forces of water adhering to surface of quartz grains resulted in higher soil water content (McKissock et al., 2002). Due to the high infiltration rate of sandy soil in the control the irrigation water moved rapidly downward and accumulated at the bottom of the containers resulted in high soil water content at 45 cm soil depth in control treatment compared to overlay and incorporation treatments. The sharp decrease in soil water content of control treatment at the last month of maize experiment (Fig. 6) and the low retained water (Fig. 8) could be due to several reasons. Firstly the present of coarse sand in the maize soil is higher than cucumber soil (Table 1). Increase coarse sand resulted in high-saturated hydraulic conductivity; consequently higher water loss occurred in maize soil than in cucumber soil and resulted in sharply decreased in soil water content. Secondly, the high temperature in June–July months increased the evaporation especially from sandy soil. Thirdly, the majority of irrigation water is retained in the upper 20 cm due to high clay content.

4.5. Water use efficiency

High water use efficiency obtained from overlay and incorporation treatments compared with control in both cultivars because they consumed the lowest amount of water (Table 2). Comparing the yield production and water consumption of the treatments revealed that adding little amount of clay content can save large amount of irrigation water. The overlay and incorporation treatments saved about 49% and 45% in maize and 64% in cucumber of the irrigation water relative to control treatment.

5. Conclusions

Remarkable improvements in crop yield, water retention and water use efficiency were done in sandy soil treated with clay. The leaf area in cucumber and stem length, stem diameter and number of leaves in maize were increased in the treatments which were treated with clay. About 2.5 times of yield was obtained from those treatments compared to control. Roots grew intensively in the layers treated with clay. The incorporation treatment retained higher amount of water than control but with small differences compared to overlay treatment. The water use efficiency and water saving is highly increased by clay application. About 45%–64% of irrigation water can be saved compared to control. In conclusion overlaying or incorporating clay on or with sandy soil is a promising method for increasing yield, improving soil moisture distribution and increasing water use efficiency as well as increasing saved water.

References


Hoffmann, H.P., Turner, D.W., 1993. Soil water deficits reduce the elongation rate of emerging banana leaves but the night/day elongation ratio remains unchanged. Scientia Horticulturae 54, 1–12.


