

Effects of two types of mulch on evapotranspiration, dry matter, and water use efficiency of soybean under different soil water content

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Abstract

Application of mulch is one technique to save water consumption and increase crop production. This study aimed to clarify effects of mulches and soil moisture conditions on biomass production, actual evapotranspiration (ET), and water use efficiency (WUE) of soybean [*Glycine max* (L.) Merr.]. Soybean was planted in clay pots with living mulch of white clover (CL) and shredded paper mulch (SP). Soil water content (SWC) in the pot was individually controlled at five levels by manual irrigation. The measured plant height, LAI, and the dry matter of the soybean were largest in the higher SWC with CL, and in the moderate SWC with SP, while the plant height of the clover in CL was higher in the lower SWC. The plant height, LAI, and the dry matter of the soybean were larger with SP compared with CL mostly in all SWC levels especially after the vegetative stage. The measured ET was significantly larger with CL compared with SP mostly in all SWC levels, e.g., the average ET in the whole period was 2.59 and 3.64 (mm/d) under the second wettest SWC level (33.6% and 33.4% in average) in SP and CL, respectively. One reason was considered as transpiration by the clover in CL. Another reason was the effect of reducing soil surface evaporation by SP that was demonstrated by the smaller ET in SP compared with measured evaporation from the bare soil pot particularly in the lowest SWC. The highest WUE for seed with SP (0.115 mg/g) was in the lowest SWC, while it was in the highest SWC with CL (0.035 mg/g). This study suggested that shredded paper mulch was effective for water saving cropping system with larger WUE compared with clover living mulch by a synergistic effect of the better growth of the soybean and the smaller ET.

Key words: Clover living mulch, *Glycine max* (L.) Merr., Pot experiment, Shredded paper mulch, Water consumption

1. Introduction

Soybean is one of the primary and versatile crops worldwide (FAO, 2024). Due to the increasing global demand for soybeans not only for meals and cakes but also for feed and oil (e.g., FAO, 2022), more production is needed even under the drought condition (Chomsang *et al.*, 2020; Matsuo *et al.*, 2013b; Oya *et al.*, 2004).

First, for increasing the production and yield of soybean under the limited agricultural water, the application of mulch is one of the well-known techniques. Many types of mulch have been widely applied in crop production (e.g., Kader *et al.*, 2017). Plastic film mulches of some colors, i.e., clear, white, black, white/black, silver/black, and aluminum/black, were applied to suppress weed growth (Asiegha, 1991; Azad *et al.*, 2015; Biswas *et al.*, 2015; Shrivastava *et al.*, 1994), to conserve soil moisture and thus reduce evaporation loss from the soil surface

(Chen *et al.*, 2022; Fan *et al.*, 2017; Kumari, 2012; Li *et al.*, 2015; Miyauchi *et al.*, 2012; Moratiel and Martínez-Cob, 2012; Zhang *et al.*, 2017), to increase soil temperature in cool climate (Azad *et al.*, 2015; Fan *et al.*, 2017; Sakaigaichi *et al.*, 2021; Ruiz-Machuca *et al.*, 2014), and thereby to increase yield (Fan *et al.*, 2017; Kumari, 2012; Ruiz-Machuca *et al.*, 2014; Shrivastava *et al.*, 1994; Zhang *et al.*, 2017) and water use efficiency (WUE) (Fan *et al.*, 2017; Helmy *et al.*, 2024; Kumari, 2012; Shrivastava *et al.*, 1994; Zhang *et al.*, 2017). Despite the many effects of plastic mulches, it cannot be decomposed by microorganisms in soil (Kitou and Yoshida, 1994) and net return and benefit-cost ratio were lower than organic mulches (Biswas *et al.*, 2015; Li *et al.*, 2022; Rahman and Khan, 2001).

Advantages of organic mulches in comparison with the non-biodegradable plastic mulches were approved especially from the viewpoint of organic farming practices, while weeds were the most serious threat in organic farming systems (Uchino *et al.*, 2009). Plant residues such as hay, cut grasses, and rice, wheat, or maize straw, which are called as killed mulches or dead mulches, rice husk, sugarcane or sweet sorghum bagasse, coffee grounds, silage, sawdust, wood tips, cassava peel, and even peanut hull have been applied to achieve the same effects as in plastic film mulches and thus reduce evaporation loss from the soil surface (Li *et al.*, 2008; Ssali *et al.*, 2003), to increase soil temperature in cool climate (Kitou and Okuno, 1997), to

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decrease soil temperature in hot climate (Gaur and Mukherjee, 1980), to activate the growth of the crop (Asagi *et al.*, 2015; Kader *et al.*, 2019), to increase yield (Asiegha, 1991; Awad *et al.*, 2024; Biswas *et al.*, 2015; Gaur and Mukherjee, 1980; Kaur and Brar, 2016; Hirooka *et al.*, 2021; Kitou and Okuno, 1997; Miyasaka *et al.*, 2001; Shrivastava *et al.*, 1994; Ssali *et al.*, 2003; Tang *et al.*, 2013; Zhang *et al.*, 2015) and WUE (Biswas *et al.*, 2015; Li *et al.*, 2022; Zhang *et al.*, 2015), and to enrich nutrition (Asagi *et al.*, 2015; Biswal *et al.*, 2024; Hirooka *et al.*, 2021; Juang *et al.*, 2021; Yamane *et al.*, 2014). Despite these advantages of dead mulches, Li *et al.* (2008) showed that WUE of winter wheat with straw mulch decreased, while evapotranspiration (ET) decreased, due to the decreased spike number that was caused by the decreased soil temperature.

The pre-planted cover crop that is grouped into living mulch is also one of the options of organic mulches. The pre-planted Poaceae, Leguminosae, and Asteraceae cover crops have been successfully applied to achieve the same effects as in plastic film mulches and dead mulches (Rühlemann and Schmidtke, 2016; Salako and Tian, 2003; Sung *et al.*, 2010; Uchino *et al.*, 2011), to enrich nutrition as green manure (Anugroho *et al.*, 2010; McVay *et al.*, 1989; Uchino *et al.*, 2011), to improve soil physical properties such as infiltration (McVay *et al.*, 1989), and to save labour by minimized or no tillage (Rühlemann and Schmidtke, 2016). The pre-planted cover crop, however, has been also reported to suppress the growth of the main crop through competition for water and nutrient (Uchino *et al.*, 2011).

The cover crop interseeded or interplanted into the main crop is another option of living mulch to prevent the competition in the pre-planted cover crop techniques stated above (Abdin *et al.*, 2000; Asagi *et al.*, 2008; Uchino *et al.*, 2011). The interseeded cover crops of Leguminosae such as milk vetch, hairy vetch, and some types of clover, and Poaceae such as winter rye have been successfully applied as living mulch to aim the same effects as in the other types of mulches (e.g., Asagi *et al.*, 2008; Latif *et al.*, 1992; Uchino *et al.*, 2012, 2015) and to increase the yield of main crops (Samarajeewa *et al.*, 2005), and to function these effects without causing yield reduction of main crops (White and Scott, 1991) if weed pressure was low (Ateh and Doll, 1996), under conditions of adequate rainfall (Abdin *et al.*, 2000), and when the cover crop was sown after main crop planting (Uchino *et al.*, 2009).

On the other hand, no effects (Moomaw, 1995) and even less yields (White and Scott, 1991) or less above-ground dry matter (Thorsted *et al.*, 2006) compared with no mulch treatment were presented for interseeded cover crops as living mulch. Moreover, challenges to reduce the competition for light (den Hollander *et al.*, 2007; Uchino *et al.*, 2009), nutrient (Feil *et al.*, 1997; Thorsted *et al.*, 2006; Uchino *et al.*, 2009; White and Scott, 1991), and water (Ateh and Doll, 1996) were critically posed (Uchino *et al.*, 2011). Therefore, very little has been clarified yet about competitions between the main crop and cover crop in this interseeding system (Thorsted *et al.*, 2006).

Another alternative mulching technique for no herbicide cultivation to the plastic mulch is using recycled-paper or newspaper as mulch (Ueno *et al.*, 1999). Paper mulching was successfully applied to suppress weed growth that served to save

labour by direct seeding of rice (Ueno *et al.*, 1999), to conserve soil moisture, and to increase the yield of main crops (Kader *et al.*, 2019).

Next, from the viewpoint of soil moisture condition for soybean, the yield of soybean is limited by soil moisture fluctuation from flooding to drought (Matsuo *et al.*, 2013a). Basically, water stress in vegetative (Rosadi *et al.*, 2007) and reproductive stages leads to the reduction of yield (Chomsang *et al.*, 2020), although the drought tolerance has been recognized as different between cultivars (e.g., Matsuo *et al.*, 2013a; Oya *et al.*, 2004). More in precise, water stress conditions during flowering and pod growth stages (Lal *et al.*, 1999), early pod formation and pod filling stage (Oya *et al.*, 2004), or seed growth stage (Saitoh *et al.*, 1999) considerably slowed down the potential reproductive growth and were critical for biomass production and seed yield. Chomsang *et al.* (2020) revealed positive linear relationships between the total amount of irrigation and total dry matter, but the largest physiological WUE (= photosynthetic rate / transpiration rate) was obtained not under field capacity (Fc) but under 80% of Fc condition. Excessive soil moisture, flooding stress, or waterlogging especially in Japanese crop rotation with rice cultivation caused delayed stem senescence (Sato *et al.*, 2007) and reduction of growth and yield (Jung *et al.*, 2008; Matsunami *et al.*, 2007; Matsuo *et al.*, 2013a; Sugimoto *et al.*, 1988; Uchikawa *et al.*, 2003). Despite these disadvantages of drought and flooding, soil moisture deficit in pre-flowering stage had a well-developed root system (Hirasawa *et al.*, 1998), and an acclimation mechanism to flooding stress (Shimamura *et al.*, 2002) was also found. Accordingly, effects of different soil moisture conditions on the growth of soybean are still debatable (Shimada *et al.*, 1995, 2012; Uchikawa *et al.*, 2003).

This study focused on effects of mulches on growth, biomass production, actual ET, and WUE of soybean planted in pots under five different soil moisture levels. Despite a lot of studies for functions by applying a variety of mulches, challenges for comparisons of living and non-living mulches in production, ET, and WUE under different soil moisture conditions have novelty. Applied mulches for this study were clover living mulch as an interseeded cover crop and shredded paper mulch.

2. Materials and methods

2.1. Materials for experiments

The experiment with soybeans planted in clay pots (Fig. 1) was conducted in a glasshouse (7.2 m in the north-south and 12.8 m in the east-west) to avoid cold stress (Kurosaki and Yumoto, 2003; Saito *et al.*, 1970) and control soil moisture by keeping rain out, in Faculty of Agriculture, Ehime University, Japan (33.83°N, 132.79°E) from December 2019 to May 2020. The sliding doors and windows of the glasshouse were usually closed but not completely as those had some cracks that helped to have natural ventilation. The reasons for the pot-planted experiment were to control soil water content (SWC) of each pot in five levels and to measure daily actual evapotranspiration (ET) of 42 pots under different SWC levels by the weighing method as described in 2.2 and 2.3, which were impossible by a field experiment, despite a disadvantage of the limited space of the pot for soybean.

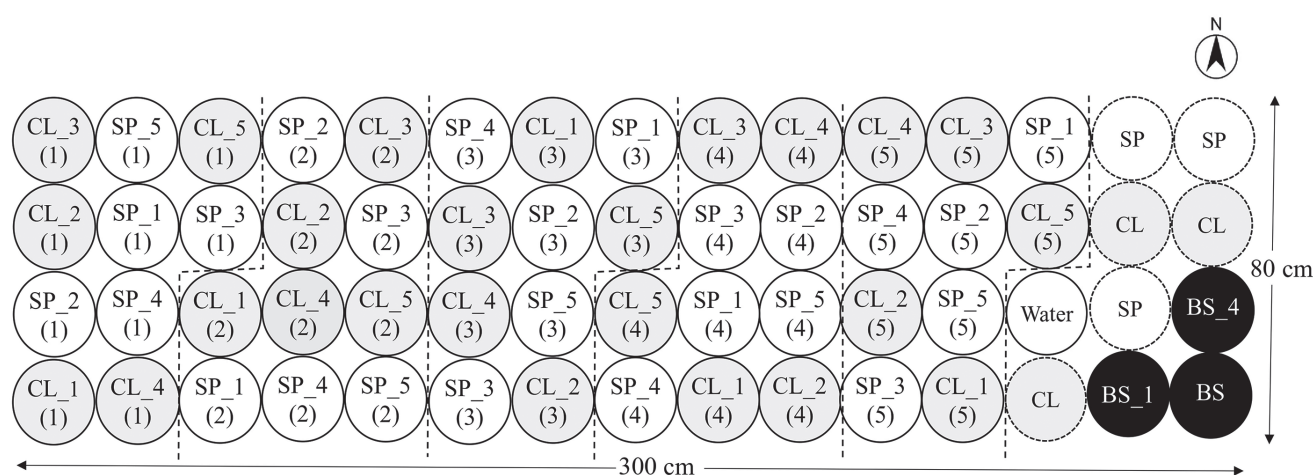


Fig. 1. The arrangement of pots in the glasshouse with CL (gray) and SP (white) of soybean and without soybean (10 pots in the east edge). Replication number was within brackets. For example, “CL_3 (2)” meant the second replication of soybean pot with CL in SWC-3. The eight pots in the east edge without SWC level and “Water” were not used for measurements.

Soybean seeds of determinate-type soybean [*Glycine max* (L.) Merr. 'Otofuke Oosode'] were sown on December 3, 2019, and three seedlings were transplanted to clay pots on December 13. By considering the weather condition in winter-to-spring season, this cultivar that had been developed in Hokkaido, i.e., north Japan was selected. The pots had a hole at the bottom, with an inside diameter of 20.5 cm at the top, 17.5 cm height and a volume of 3544 cm³. The soil, consisting of 1.00 kg black soil and 3.00 kg biochar (charcoal derived from rice husks) that corresponded totally to a volume of 2510 cm³, was put into each pot. Combined fertilizer (N: P₂O₅: K₂O = 5:15:15) of 3.08 g/pot was added as basal fertilizer. The resulting diameter of the soil surface in the pot was 20.0 cm and the depth was around 14.0 cm. The soybean plants were thinned to one plant/pot, on January 3, i.e., 21 days after transplanting (DAT). The resulted planting density was 31.8 plants m⁻² that was denser than in a standard field; 10 to 20 plants m⁻² (Chomsang *et al.*, 2021; Miyauchi *et al.*, 2012; Saryoko *et al.*, 2017).

This study applied two types of mulch, i.e., a living mulch of white clover (CL) as an interseeded cover crop and shredded paper mulch (SP). For CL, about 580 seeds (2.00 g) of white clover [*Trifolium repens* (L.)] were sown in each pot. In some previous studies, interseeded cover crops were sown on the different days of sowing main crops. In this study, white clover was sown on the same day as the soybean was transplanted by following to Uchino *et al.* (2009) that cover crop was sown after main crop had been sown. For SP, 37.0 g corresponding to 1177.8 g/m² of shredded used copier paper (shredded pieces were 3.6 cm × 0.3 cm) was spread out to completely cover the soil surface in each pot. Soybean was grown with CL in 25 pots and with SP in 25 pots. The soybean was harvested from the end of April to the middle of May.

The measurements until April 30, 2020 were analyzed by dividing growth stages of the soybean into three, i.e., the vegetative (from V1 to V6) stage (December 27, 2019–February 13, 2020, i.e., DAT 14–62) corresponding to BBCH (Meier, 2001) 11–19 denoted as ‘Stage 1’, from the beginning flowering (R1) to the beginning pod (R3) stage (February 14–March 19,

i.e., DAT 63–97) corresponding to BBCH 60–70 as ‘Stage 2’, and from the full pod (R4) to beginning maturity (R7) stage (March 20–April 30, i.e., DAT 98–139) corresponding to BBCH 71–89 as ‘Stage 3’.

2.2. Soil moisture conditions applied to the pots and irrigation protocol

The arrangement of each pot was shown in Fig. 1. The pots were put on a table of 4.4 m × 1.0 m × 0.4 m (L/W/H) to prevent heat exchange with the floor. Each pot was put on a plastic tray to catch drained water. All the pots were fully irrigated every morning until the first trifoliolate (V1) stage of the soybean, i.e., DAT 11 (December 24). After the day, the manual control of the soil moisture condition was started to achieve five different levels around 20%, 20%–25%, 25%–30%, and 30%–35% of volumetric soil water content (SWC), and near-saturated condition, by monitoring SWC every morning, and each pot was intermittently irrigated. The five SWC levels were denoted as SWC-1 to SWC-5 in the order from the driest to the wettest moisture condition. Each SWC level had five pots for replication with both CL and SP. In addition to the soybean pots of CL and SP, soil pots without mulch and soybean, i.e., bare soil (BS) for SWC-1 and SWC-4 were treated in the same ways as for CL and SP. In Fig. 1, the replications were shown in the brackets. For example, “CL_3 (2)” meant the second replication of CL in SWC-3. For the arrangement, pots were grouped into five blocks in accord with replicate numbers (broken lines were drawn between each block in Fig. 1). The other pots such as BS and spares of CL and SP were grouped in one block in the east edge. Among 10 pots of the east edge block, just BS_1 and BS_4 were applied to measurements. For avoiding confusion, this paper did not describe about the pots with CL and SP without soybean hereafter. To each block, the randomized complete block design was applied, and the position of each pot was assigned by drawing slips of paper.

The SWC was measured for the five replications with CL and SP, and the two BS pots every morning using a capacitance type soil moisture sensor (Model 5TE, METER, USA) that had

a quick response. The sensor was temporarily installed into the soil of each pot so that the 6 cm sensor rods could be completely within the soil by paying attention the installed point could be at least around 7 cm apart from the pot edge and not on the base of soybean. Data were monitored and noted manually using a hand-held reader (Model ProCheck, METER, USA) when the readings became stable. If the measured SWC reached around the projected minimum, i.e., 10%, 15%, 20%, 28% and 30%, respectively for SWC-1 to SWC-5, the pot was irrigated by pouring water from a measuring cylinder slowly on the soil surface until excessive water was drained from the bottom of the pot and collected by the tray. Irrigation in mm was obtained by the input water volume minus drained water volume divided by the soil surface area. Hereafter, each SWC level with each mulch and without mulch is called 'treatment'.

2.3. Methods of measurement and analysis

Meteorological conditions, i.e., solar radiation (St) by Model PYR (METER, USA) and air temperature (Ta) and relative humidity of air (RH) by Model VP-3 (METER, USA), which was housed in a radiation shield, were measured at 2.0 m height from the floor surface in the glasshouse from December 13, and were recorded every minute by a data logger (Model Em50, METER, USA).

Daily actual ET of four replications with CL and SP and actual evaporation of the two BS (42 pots in total) in mm were measured from December 27, 2019 and January 1, 2020, respectively, until May 1, 2020 by the net daily change in pot weight divided by the soil surface area. These pots were weighed using an electric balance (Model EP-22KA, AND, Japan) at a precision of 1.0 g every morning around from 8:00 to 9:00 JST before and after irrigation. Among many ways for potential evaporation (Ep) under the given meteorological conditions on site, this study simply calculated Ep by the equation (1) referring to de Bruin (1987) and de Bruin and Lablans (1998) originally based on Makkink equation (Makkink, 1957) that did not need wind speed. By the equation (1), hourly Ep (mm h^{-1}) during the period in $St > 0$ was calculated and accumulated to the daily Ep (mm d^{-1}).

$$Ep = 3.6 \Delta St / [Lv (\Delta + \gamma)], \quad (1)$$

$$Lv = 2499 - 2.512 Ta, \quad (2)$$

where Δ ($\text{hPa } ^\circ\text{C}^{-1}$) is the slope of the saturated vapour pressure curve at Ta ($^\circ\text{C}$), γ is the psychrometric constant ($= 0.66 \text{ hPa } ^\circ\text{C}^{-1}$), and Lv (J g^{-1}) is the heat of vaporization at Ta ($^\circ\text{C}$).

Plant height (PH) of the soybean in each treatment was obtained by averaging the measurements of five replications, once a week from January 5 after the soybean plants were thinned to one plant/pot. PH of the clover in CL pots under each SWC level was also measured in the same way as for the soybean, but once to three times a week from January 26. Leaf area index (LAI) of the soybean in each treatment was obtained by averaging the estimated leaf areas of three replications and by dividing by the soil surface area in the pot, once a week from February 23. Each leaf area (LA) was estimated by $LA = \alpha WL$, where W and L were the width and length of each leaf, respectively, that were measured by a ruler on site. The parameter $\alpha = 0.716$ ($R^2 = 0.998$) was obtained by measuring

LA, W , and L of seven leaves by sampling. LA of the sampled leaves was measured manually by placing the leaf on a grid paper sheet of 1 mm^2 , tracing the outline of the leaf, and counting the total grid squares.

For investigating biomass production, the aboveground dry matter (DM, g/pot) of leaves, stems, seeds, and pods of the soybean was measured by harvesting all five plants in each treatment and drying the sampled plants in an oven at 80°C for 48 h.

Water use efficiency of the soybean (WUE , mg/g) was estimated for the total aboveground DM (WUE_{total}) and for seed DM (WUE_{seed}) of the soybean, by dividing each DM by the total ET in the whole targeted growth period.

For multiple comparison of results between the five different SWC levels, or between the two mulches and without mulch, Bonferroni correction was applied to a double-sided t-test. This method has been a commonly utilized process although it has been also recognized as conservative because it becomes more unlikely to find significance due to the Type II error under the condition of larger tables of statistical tests (e.g., Moran, 2003).

3. Results and discussion

3.1. Meteorological conditions

The measured timely variations of daily total solar radiation (St) with the accumulated St , daily average air temperature (Ta) with the accumulated Ta , and relative air humidity (RH) were shown in Fig. 2(a)–(c). The calculated timely variation of daily potential evaporation (Ep) was shown in Fig. 2(d). Due to the season's transition, St and Ta showed increasing trends and RH showed decreasing trend as a whole. Having been affected by the trends of these climatic conditions, Ep showed an increasing trend. The average Ta was 13.6, 16.7, and 20.6 ($^\circ\text{C}$) in Stages 1, 2, and 3, respectively. The accumulated daily average Ta was 874.2, 585.2, and 866.6 ($^\circ\text{C days}$) in Stages 1, 2, and 3, respectively, and 2326.0 ($^\circ\text{C days}$) in the whole targeted period from December 13 to April 30. The daily average Ta was lower than the optimum Ta of 25°C for grain number and grain weight concluded by Uchikawa *et al.* (2003). Meanwhile, maximum Ta over 30°C within the glasshouse that was observed from March might have given thermal stress to soybean (Egli *et al.*, 2005; Dornbos and Mullen, 1991; Gibson and Mullen, 1996; Lal *et al.*, 1999). The accumulated St was 352.6, 275.7, and 449.7 (MJ m^{-2}) in Stages 1, 2, and 3, respectively, and 1078.0 (MJ m^{-2}) in the whole targeted period.

3.2. Irrigation interval and soil water content

The averaged soil water content (SWC) and irrigation intervals in each treatment in each growth stage were summarized in Tables 1 and 2, respectively. Daily variations of SWC of soybean pots (a) with CL and (b) with SP, and (c) bare soil (BS) pots in each SWC level, which were measured every morning, were shown in Fig. 3(a)–(c). As explained above, SWC in each pot was manually controlled by targeting the five levels. The pots of SWC-5 were irrigated mostly every day, while the pots of SWC-1 were irrigated with the longest interval among all SWC levels. Thus, for keeping a lower SWC level, less frequent irrigation was applied, which resulted in a wider range of the

SWC variation compared with a higher SWC level in the whole targeted period (Fig. 3). The near-saturated SWC-5 would have been close to field capacity (Fc) condition because of mostly every morning irrigation, although SWC corresponding to Fc

had not been confirmed. Assuming SWC-5 as in Fc condition, SWC-4, 3, 2, and 1 corresponded averagely to 91%–93%, 78%–81%, 70%–73%, and 64%–65% of Fc, respectively (Table 1).

Comparing the irrigation intervals between CL and SP, the interval for CL was shorter compared with SP in any SWC level in all stages. This suggested that the soybean pots with CL consumed a larger amount of water through evapotranspiration consisting of transpiration by both the soybean and clover, and soil surface evaporation, while the soybean pots with SP could have prevented soil surface evaporation as will be discussed in 3.4. Comparing the irrigation intervals in each treatment from stage to stage, the interval became shorter as the stage proceeded

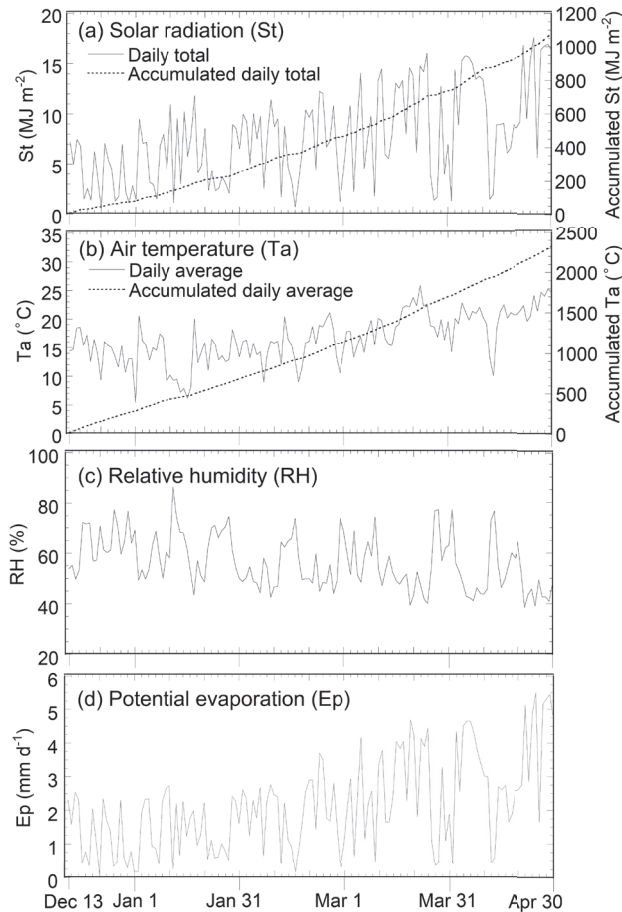


Fig. 2. Timely variations of (a) daily total solar radiation (St) with the accumulated St , daily averaged (b) air temperature (Ta) with the accumulated Ta and (c) relative air humidity (RH), and (d) daily potential evaporation (Ep) from December 13, 2019 to April 30, 2020.

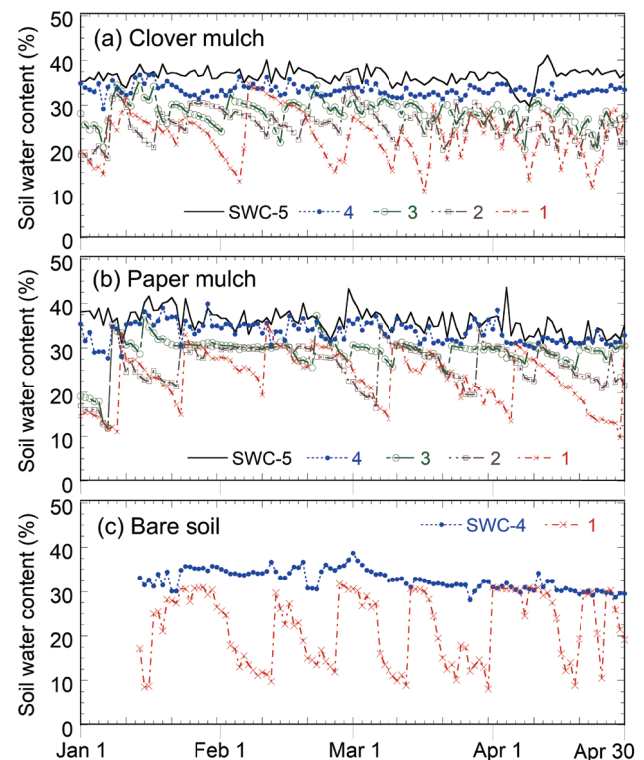


Fig. 3. Daily variations of SWC of soybean pots (a) with CL and (b) with SP, and (c) bare soil (BS) pots in each SWC level.

Table 1. The averaged soil water content (SWC in %) in the soybean pots with the clover mulch (CL) and the paper mulch (SP), and in the bare soil (BS) pots, in each soil water content (SWC) level in each growth stage and the whole targeted growth period (Total). Sample standard deviations were shown under SWC values.

Mulch type	CL (%)					SP (%)					BS (%)	
SWC level ¹⁾	SWC-5	SWC-4	SWC-3	SWC-2	SWC-1	SWC-5	SWC-4	SWC-3	SWC-2	SWC-1	SWC-4	SWC-1
Stage 1 ²⁾	36.8	33.8	28.7	26.0	24.4	37.1	34.4	28.9	25.9	23.7	34.0	21.6
	1.2	1.6	3.2	4.1	5.8	2.3	2.7	5.7	5.8	6.7	1.6	8.1
Stage 2 ²⁾	36.6	33.1	29.5	26.7	22.5	36.5	34.2	29.5	27.6	26.1	33.9	21.7
	1.5	1.1	2.2	3.1	5.3	2.3	1.8	2.3	4.4	4.7	2.0	7.9
Stage 3 ²⁾	36.3	33.1	27.3	24.4	22.7	34.2	32.2	28.9	25.5	20.8	30.7	22.1
	2.3	0.9	2.5	2.9	4.6	2.7	1.8	1.6	3.7	5.4	1.1	8.0
Total	36.6	33.4	28.4	25.7	23.2	35.9	33.6	29.1	26.3	23.4	32.7	21.8
	1.7	1.3	2.8	3.5	5.3	2.8	2.4	3.8	4.8	6.1	2.2	7.9

¹⁾ The projected volumetric soil water content (SWC) levels SWC-5, 4, 3, 2, and 1 were around 35–40, 30–35, 25–30, 20–25, and 20%, respectively.

²⁾ Stages 1, 2, and 3 correspond to the vegetative stage, from the beginning flowering to the beginning pod stage, and from the full pod to beginning maturity stage, respectively.

for all treatments except for SWC-1 of SP, and SWC-4 and SWC-1 of BS. This suggested that water consumption by evaporation and transpiration increased with the process of the stage due to the growth of soybean in CL and SP and of clover in CL, and the increase of E_p caused by increased St and T_a .

3.3. Plant height, LAI, and dry matter

Weekly variations of plant height (PH) of soybean with (a) CL and (b) SP in each SWC level were shown in Fig. 4. In most treatments, PH reached highest in the middle of March that corresponded to the full bloom stage (R2) as the determinate soybean is regarded to finish the vegetative growth in and just after the flowering stage (Kansas State University Agricultural

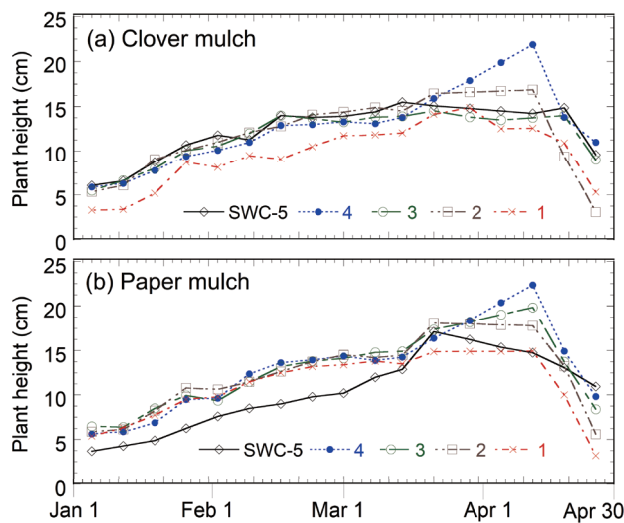


Fig. 4. Weekly variations of plant height (PH) of soybean with (a) CL and (b) SP in each SWC level.

Experiment Station and Cooperative Extension Service, 2016; Nakano *et al.*, 2020). The highest PH in each treatment was lower compared with other studies, such as 28.0–65.0 cm of 24 cultivars (Matsuo *et al.*, 2016). The shallow soil depth of the pot for roots and lower T_a compared with the optimum would have limited the soybean's growth regardless of the treatments. The averaged PH in each treatment in each growth stage and the whole targeted growth period was summarized with the statistical significance at the 0.05 level by a double-sided t-test of a paired sample with Bonferroni correction in Table 3. The statistical significance of PH between CL and SP in each SWC level was also analyzed but not shown in Table 3.

Firstly, with CL, comparing between each SWC level in Stages 1 and 2, PH in SWC-5 was highest but not significantly higher compared with SWC-2 and 3, while PH in SWC-1 was significantly lowest. In Stage 3, PH in SWC-4 was significantly highest. In the whole targeted growth period, PH in SWC-4 was highest, while PH in SWC-1 was significantly lowest. Secondly, with SP, comparing between each SWC level in all stages, PH in the moderate SWC conditions, i.e., SWC-2 to SWC-4 was higher partly significantly compared with the wettest (SWC-5) and the driest (SWC-1) conditions, while PH in SWC-5 was significantly lowest in Stages 1 and 2, and PH in SWC-1 was lowest in Stage 3. Thirdly, about the difference of PH between CL and SP, PH with CL in Stage 1 was significantly higher in SWC-5 but significantly lower in SWC-1 compared with SP. In Stage 2, PH with CL was still significantly higher in SWC-5 compared with SP but lower in the other SWC levels with significance in SWC-4 and SWC-1. In Stage 3, however, PH with CL became lower in all SWC levels compared with SP with significance in SWC-2.

In summarizing, PH of soybean with CL in the driest condition

Table 2. The averaged irrigation intervals (days) in the soybean pots with the clover mulch (CL) and the paper mulch (SP), and in the bare soil (BS) pots, in each soil water content (SWC) level in each growth stage and the whole targeted growth period (Total).

Mulch type	CL (days)					SP (days)					BS (days)	
SWC level ¹⁾	SWC-5	SWC-4	SWC-3	SWC-2	SWC-1	SWC-5	SWC-4	SWC-3	SWC-2	SWC-1	SWC-4	SWC-1
Stage 1 ²⁾	1.3	1.5	7.6	23.6	20.0	1.4	1.8	21.7	32.5	26.0	2.4	6.5
Stage 2 ²⁾	1.1	1.4	7.0	12.5	15.9	1.2	1.6	15.9	17.5	29.2	1.8	11.7
Stage 3 ²⁾	1.0	1.1	3.9	4.6	7.5	1.1	1.2	8.4	17.5	26.3	1.4	14.0
Total	1.2	1.3	5.7	9.1	12.4	1.2	1.5	13.4	21.5	26.9	1.8	9.2

¹⁾ The SWC levels were the same as in Table 1.

²⁾ Stages 1, 2, and 3 were the same as in Table 1.

Table 3. The averaged plant height (cm) of the soybean with the clover mulch (CL) and the shredded paper mulch (SP) in each soil water content (SWC) level in each growth stage and the whole targeted growth period (Total). Different letters beside the values indicated significant differences ($p < .05$) among the five SWC levels in each mulch by a double-sided t-test of a paired sample with Bonferroni correction.

Mulch type	CL (cm)					SP (cm)				
SWC level ¹⁾	SWC-5	SWC-4	SWC-3	SWC-2	SWC-1	SWC-5	SWC-4	SWC-3	SWC-2	SWC-1
Stage 1 ²⁾	9.2 a	8.4 abcd	8.8 abc	9.0 ab	6.4 e	5.9 e	8.3 abcd	8.7 ab	8.9 a	8.4 abc
Stage 2 ²⁾	14.3 a	13.2 bcd	13.7 abc	14.1 ab	11.1 e	10.8 cde	14.0 ab	14.2 a	13.9 abc	13.3 bcd
Stage 3 ²⁾	13.9 ab	16.7 a	13.1 abcd	13.2 abc	11.7 bcde	14.6 abcd	17.0 a	16.1 ab	15.1 abc	12.1 de
Total	12.4 ab	12.8 a	11.8 abcd	12.0 abc	9.6 e	10.4 de	13.1 a	12.9 ab	12.6 abc	11.2 d

¹⁾ The SWC levels were the same as in Table 1.

²⁾ Stages 1, 2, and 3 were the same as in Table 1.

(SWC-1) was lowest among the five SWC levels in all stages, while PH with SP in the wettest condition (SWC-5) was lowest in Stages 1 and 2, and lower compared with SWC-4, 3, and 2 in Stage 3. These results suggested that soybean could not grow well under the near saturated condition (SWC-5) and the very dry condition (SWC-1) due to water stress. But soybean with CL could grow quite well in SWC-5 just in Stages 1 and 2. This might have been because the competition with clover for water would have unintentionally provided a preferable condition for soybean in SWC-5.

Moreover, PH of soybean with CL was lower compared with SP in Stages 2 and 3 except for in SWC-5. The lower PH with CL would have been caused by another water stress on soybean by competing with clover for water. Meanwhile, a reason for the higher PH with CL in SWC-5 in Stages 1 and 2 compared with SP was regarded as the same reason as for quite good growth with CL under SWC-5 among the five SWC levels in Stages 1 and 2 stated above.

Weekly variations of LAI of soybean with (a) CL and (b) SP in each SWC level, of which measurements started in Stage 2, were shown in Fig. 5. With CL, LAI reached largest (e.g., 0.481 in SWC-5) from the early to the middle of March in the full bloom stage (R2) and decreased in April in all SWC levels. With SP, it reached largest from early March in SWC-1 and SWC-5, while it continued increasing even after flowering and reached largest (e.g., 0.623 in SWC-4) from late March to early April in the pod

(R3–4) stage in the other SWC levels. Due to the meteorological conditions and the limited pot size as stated above for PH, those were smaller compared with field-grown soybean such as in Kawasaki *et al.* (2018). The earlier LAI peak in CL compared with SP would be also caused by the competition with clover for water.

The averaged LAI in each treatment in each growth stage and

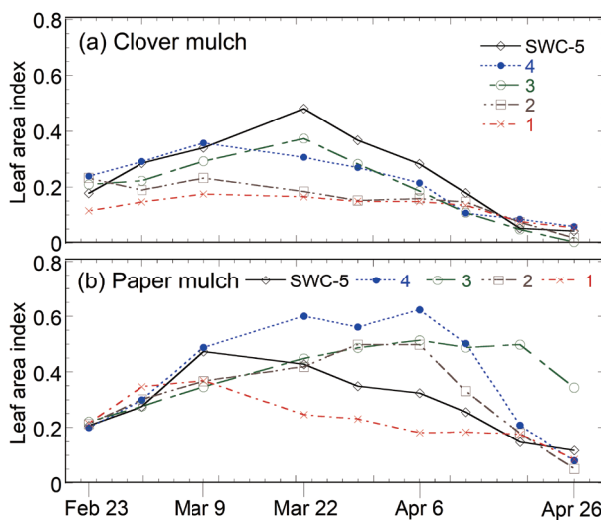


Fig. 5. Weekly variations of LAI of soybean with (a) CL and (b) SP in each SWC level.

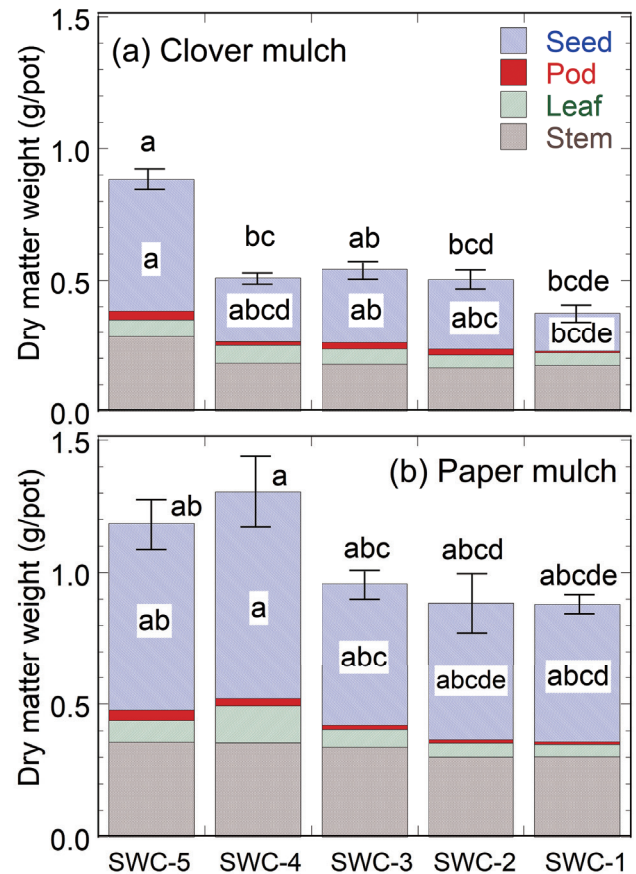


Fig. 6. Comparisons of the averaged aboveground dry matter weight (DM) of leaves, stems, seeds, and pods of the soybean per one plant in each SWC level with (a) CL and (b) SP. The standard error for the total DM was shown by the vertical line on each bar graph. Different letters above the bars and within the bar of “Seed” indicate significant differences ($p < .05$) between SWC levels in the total aboveground DM and in seeds, respectively, by a double-sided t-test for two samples of non-homovariances with Bonferroni correction.

Table 4. The averaged LAI of the soybean with the clover mulch (CL) and the paper mulch (SP) in each soil water content (SWC) level in each growth stage and the whole targeted growth period (Total). Different letters beside the values indicated significant differences ($p < .05$) among SWC levels with each mulch by a double-sided t-test of a paired sample with Bonferroni correction.

Mulch type	CL					SP				
SWC level ¹⁾	SWC-5	SWC-4	SWC-3	SWC-2	SWC-1	SWC-5	SWC-4	SWC-3	SWC-2	SWC-1
Stage 2 ²⁾	0.268 ab	0.297 a	0.241 abc	0.218 abcd	0.146 abcde	0.318 ab	0.328 a	0.280 abcde	0.293 abcd	0.310 abc
Stage 3 ²⁾	0.234 a	0.174 ab	0.167 bc	0.122 abcd	0.122 abcde	0.270 bcd	0.429 ab	0.463 a	0.329 abc	0.183 bcde
Total	0.246 a	0.215 ab	0.192 bc	0.154 abcd	0.130 abcde	0.286 abcd	0.395 ab	0.402 a	0.317 abc	0.225 abcde

¹⁾ The SWC levels were the same as in Table 1.

²⁾ Stages 2 and 3 were the same as in Table 1.

the whole targeted period was summarized in Table 4 with the statistical significance at the 0.05 level in the same way as in Table 3. The statistical significance of LAI between CL and SP in each SWC level was also analyzed but not shown in Table 4.

Firstly, with CL, in Stage 2, LAI of soybean was largest in SWC-4 and smallest in SWC-1, but the differences between in each SWC were not significant. In Stage 3 and the whole targeted growth period, LAI was largest in SWC-5 and smallest in SWC-1, but the differences between in each SWC were not mostly significant. It resulted in larger LAI in the higher SWC, and smaller LAI in the lower SWC with CL. Secondly, with SP, in Stage 2, it was largest in SWC-4 but the differences between in each SWC were not significant. In Stage 3, LAI in SWC-3 was largest and significantly larger compared with SWC-5 and SWC-1, and LAI in SWC-1 was smallest. In the whole targeted growth period, LAI was largest in SWC-3 and smallest in SWC-1, but the differences between in each SWC were not significant. Thirdly, about the difference of LAI between CL and SP, LAI of CL was smaller compared with SP in all SWC levels in all stages. In summarizing, LAI of CL was larger in the higher SWC level, similarly to the higher PH in the higher SWC levels. Meanwhile, LAI of SP was larger in the moderate SWC, i.e., SWC-2 to SWC-4, and smaller in SWC-5 and SWC-1, similarly to the differences in PH in these SWC levels.

Comparisons of the averaged aboveground DM of leaves, stems, seeds, and pods of the soybean per one pot, i.e., for one plant, taken from the five replications in each SWC level with (a) clover mulch (CL) and (b) paper mulch (SP) were shown with the statistical significance at the 0.05 level by a double-sided t-test for two samples of non-homovariances with Bonferroni correction in Fig. 6. The standard error for the total DM was shown by the vertical line on each bar graph.

Firstly, the total aboveground DM of soybean with CL was largest in SWC-5 and it was significantly larger compared with SWC-4, SWC-2, and SWC-1. The differences between the other SWC levels were not significant. It was smallest in SWC-1. With SP, the total DM of soybean was largest in SWC-4 and smallest in SWC-1, and the difference between each SWC level was not significant. Secondly, the seed DM of soybean with CL was largest in SWC-5 and smallest in SWC-1 same as for the total DM. Just the difference between SWC-5 and SWC-1 was significant. With SP, the seed DM of soybean was largest in SWC-4 and smallest in SWC-2, but the difference between each SWC was not significant. Not significantly smallest total DM in SWC-1 and seed DM in SWC-2 with SP could demonstrate a specific effect of SP to keep soybean growth even in dry condition that was related to discussion of WUE in 3.5. Thirdly, the leaf DM of soybean with CL was largest in SWC-4 nearly the same as in SWC-5 and smallest in SWC-1 nearly the same as in SWC-2 with no significance between each SWC (the significance was not included in the figure). With SP, the leaf DM of soybean was largest in SWC-4 and smallest in SWC-1, same as in the total DM with no significance between each SWC. Fourthly, both with CL and SP, the stem DM of soybean was largest in SWC-5 (nearly the same as in SWC-4 with SP) and smallest in SWC-2 nearly the same as in SWC-1. The pod DM of soybean was largest in SWC-5 and smallest

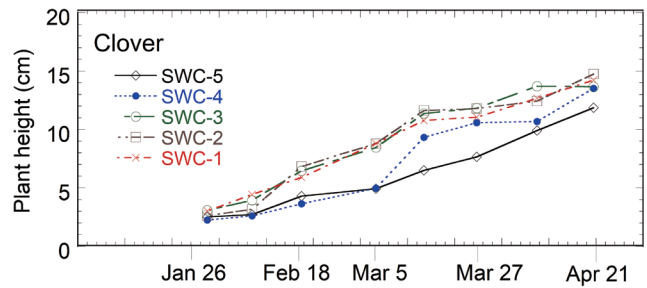


Fig. 7. Timely variations of the plant height of the clover of CL in each SWC level averaged nearly every two weeks.

in SWC-1 both with CL and SP. The significances in the stem and pod DMs between SWC levels and between mulches could not be analyzed as the harvested stems and pods of five plants were mixed in each treatment. Fifthly, each DM and the total aboveground DM of soybean with SP were larger compared with CL in all SWC levels except for leaf DM in SWC-1 (ns) and pod DM in SWC-2 and SWC-3. The total DM of soybean with SP was significantly larger compared with CL in SWC-1 and SWC-3. The seed DM with SP was significantly larger compared with CL in SWC-1.

Variations of PH of the clover in CL pots under each SWC level, measured once to three times a week and averaged nearly every two weeks, were shown in Fig. 7. For example, the data plotted on February 8 in the figure (the second place from the left) were averages of the measurements on February 5, 8, and 11. The clover in all SWC levels continued growing even after the soybean reached the beginning seed (R5) stage, when PH and LAI of the soybean had already started decreasing. The averaged PH of the clover in CL in each SWC in each growth stage and the whole targeted growth period were summarized in Table 5 with the statistical significance at the 0.05 level in the same way as in Table 3. It was mostly higher in the lower SWC levels and lower in the higher SWC levels in any stage. The differences between the higher PH (in SWC-1 to SWC-3) and lower PH (in SWC-5 and SWC-4) were partly significant. In the whole targeted period (Total), PH was highest in SWC-3, followed by SWC-2, and lowest in SWC-5. Therefore, clover thrived in low SWC while soybean declined, which should have caused

Table 5. The averaged plant height (cm) of the clover used for the mulch in the soybean pots (CL) in each soil water content (SWC) level in each growth stage and the whole targeted growth period (Total). Different letters beside the values indicated significant differences ($p < .05$) among SWC levels with each mulch by a double-sided t-test of a paired sample with Bonferroni correction.

	(cm)				
SWC level ¹⁾	SWC-5	SWC-4	SWC-3	SWC-2	SWC-1
Stage 1 ²⁾	2.6 abcd	2.5 cde	3.6 ab	3.0 abc	3.9 a
Stage 2 ²⁾	5.1 de	5.6 d	8.5 ab	8.8 a	8.2 abc
Stage 3 ²⁾	9.8 de	11.6 abcd	13.1 ab	13.1 a	12.7 abc
Total	6.7 de	7.6 d	9.6 a	9.6 ab	9.4 abc

¹⁾ The SWC levels were the same as in Table 1.

²⁾ Stages 1, 2, and 3 were the same as in Table 1.

negative synergistic water stress for soybean.

The results of PH, LAI, and DM of the soybean can be summarized as follows. Firstly, the soybean with SP grew better than with CL mostly in all SWC levels. Secondly, comparing the growth of soybean between each SWC level, with SP, the soybean grew better in the moderate SWC and worse in both the lowest and highest SWC, while with CL, the soybean grew better in the higher SWC and worse in the lower SWC. Considering the results in the previous studies of Meckel *et al.* (1984), Hirasawa *et al.* (1994), Shimada *et al.* (1995), Uchikawa *et al.* (2003), Matsunami *et al.* (2007), Sato *et al.* (2007), Matsuo *et al.* (2013a), and Chomsang *et al.* (2020), the best SWC with SP in this study can be regarded to be reasonable. Meanwhile, the best growth of soybean with CL in the wettest soil moisture condition would be caused by a competitive water use of soybean with the interseeded clover, which would have resulted in supplying the most preferable condition to soybean in SWC-5.

Although the water stress is one of the most critical constraints also on the growth of white clover (Barbour *et al.*, 1996), clover plants were reported to reduce flower number and accelerate vegetative growth that fails to mature under the high soil moisture condition (Adachi and Suzuki, 1968; Kagawa *et al.* 1965). Moreover, the roots, especially the taproots of clover were reported to grow and extend better in the drier soil moisture condition compared with the wetter condition (Caradus *et al.*, 1990; Woodfield and Caradus, 1987). The middle and drier moisture conditions (SWC-3, SWC-2, and even SWC-1) presented in this study, which served higher PH of the clover compared with the wetter moisture conditions, corresponded to the conditions that Kagawa *et al.* (1965) and Adachi and Suzuki (1968) had shown as the best for the growth of clover plants. Considering the clover could grow better in the lower SWC compared with the SWC preferable for the soybean, there would be a possibility that the soybean with CL in the lower SWC suffered from an negative synergistic effect of water stress and competitive water use with the clover.

3.4. Evapotranspiration and evapotranspiration ratio

The analysis of measured ET and calculated Ep were presented by using data after January 3 when the soybean plants were thinned to one plant/pot. Weekly variations of an evapotranspiration ratio (ET/Ep) with (a) CL and (b) SP in each SWC level were shown in Fig. 8. For example, the data plotted on January 6 were averages of the measurements from January 3 to 9. In addition, for evaluating effects of each mulch on water consumption, ET/Ep of CL, SP, and BS in (a) SWC-4 and (b) SWC-1 were shown in Fig. 9. In case of BS, ET/Ep is an evaporation ratio. To investigate the timely trend of ET/Ep throughout the period in each treatment, linear regressions for SP and BS, and the quadratic regression for CL were applied (Fig. 9).

As discussed with Fig. 2(d), Ep calculated by Eq. (1) could be regarded as a reference evaporation that was influenced just by the given St and Ta conditions. Meanwhile, ET is normally influenced by the conditions of soil moisture, the soil surface with or without mulch, and the vegetation, other than the given meteorological conditions. Therefore, ET/Ep was presented for

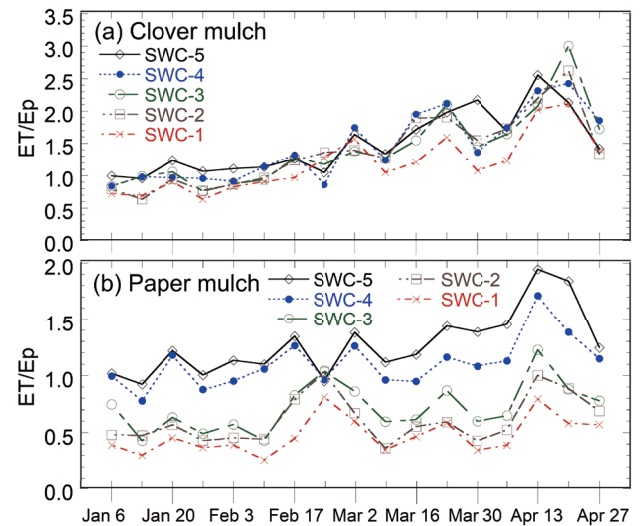


Fig. 8. Weekly variations of evapotranspiration ratio (ET/Ep) with (a) CL and (b) SP in each SWC level.

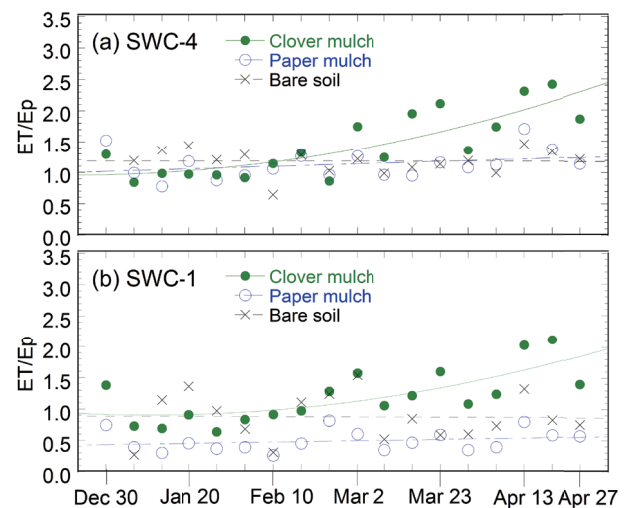


Fig. 9. Weekly variations of ET/Ep of CL, SP, and BS in (a) SWC-4 and (b) SWC-1. Each regression equation below was obtained by giving x as day numbers after $x = 0$ on December 21.

For (a) SWC-4,

$$\text{CL: } y = 0.957 + 2.878\text{E-}4 x + 8.198\text{E-}5 x^2 \quad (R^2 = 0.680),$$

$$\text{SP: } y = 1.003 + 1.932\text{E-}3 x \quad (R^2 = 0.095),$$

$$\text{BS: } y = 1.183 - 3.968\text{E-}5 x \quad (R^2 = 0.498\text{E-}4).$$

For (b) SWC-1,

$$\text{CL: } y = 0.928 - 2.915\text{E-}3 x + 8.120\text{E-}5 x^2 \quad (R^2 = 0.533),$$

$$\text{SP: } y = 0.421 + 1.070\text{E-}3 x \quad (R^2 = 0.057),$$

$$\text{BS: } y = 0.884 - 2.036\text{E-}4 x \quad (R^2 = 0.378\text{E-}3).$$

investigating the timely change of water consumption under the different SWC and the soil surface conditions, with the growth of the soybean and the clover. The averaged ET of CL and SP in each SWC level and Ep in each growth stage were summarized with those in the whole targeted growth period (Total) in Table 6. The statistical significances at the 0.05 level between each SWC level individually in CL and SP by a double-sided t-test of a paired sample with Bonferroni correction were also shown. The statistical significance of ET between CL and SP in each SWC level was also analyzed but not shown in Table 6. The relevant

summaries for CL, SP, and BS in SWC-4 and SWC-1 were shown in Table 7, which redisplayed ET of CL and SP after Table 6 for showing the statistical significances of ET between CL, SP, and BS.

Firstly, outlines of timely trends in ET/Ep (Figs. 8 and 9) were characterized as follows. The ET/Ep of the soybean pots both with CL and SP in all SWC levels showed increasing trends with time, even at small increasing rates for SP, especially after the end of January, which corresponded to the latter stage of vegetative growth. The ET/Ep both with CL and SP reached maximum in the middle of April, which corresponded to the beginning seed (R5) stage. Before the end of January, on the other hand, ET/Ep kept quite constant value for each treatment. A near constant evapotranspiration ratio is characterized in the initial growth stage of crops since transpiration accounts for a very small part of ET (e.g., Oue and Laban, 2020). In the period, the size of clover plant in the CL pots was also small enough as in Fig. 7 to ignore transpiration. Secondly, differences in ET and ET/Ep between CL and SP were characterized as follows. The increase rate of ET/Ep with time was larger in CL compared with SP that was clearly demonstrated as each regression line in Fig. 9. Although the statistical significance of ET between CL and SP in each SWC level was not shown in Tables 6 and 7, ET with CL was larger compared with SP in all SWC levels significantly ($p < .05$), except for SWC-5 and SWC-4 in Stages 1 and 2. For example, the average ET in the whole period (Table 6) was 2.59 and 3.64 (mm/d) in SWC-4 (33.6% and 33.4% in average; Table 1) in SP and CL, respectively. Thirdly,

differences in ET and ET/Ep under the different SWC levels were characterized as follows. With SP, ET and ET/Ep were larger in the higher SWC throughout the growth period, and significant differences were found between some SWC levels as shown in Table 6 and Fig. 8(b). Meanwhile, with CL, ET was not necessarily larger in the higher SWC, i.e., largest in SWC-5 (Stage 1), SWC-2 (Stage 2), SWC-3 (Stage 3), and SWC-4 (Total), but smallest in SWC-1 in all stages. The larger ET with CL in the moderate SWC conditions compared with SWC-5 would have been the effect of transpiration by clover of which plant height was higher although soil surface evaporation would have been smaller. But significant differences in ET between each SWC level with CL were rarely found as shown in Table 6. Therefore, ET/Ep with CL was not very significantly different between each SWC level, and ET/Ep was large even in the driest condition (SWC-1) as shown in Fig. 8(a). When ET/Ep and its increase rate with time were compared between SWC-4 and SWC-1 (Fig. 9), those in SWC-4 were larger compared with SWC-1 both with CL and SP as shown in the regression equations. Fourthly, differences in ET and ET/Ep of CL and SP compared with those of BS were characterized as follows. ET/Ep of BS both in SWC-4 and SWC-1 (Fig. 9) showed nearly constant through the whole targeted growth period as also shown by the regression equations, which demonstrated that ET/Ep of BS had comprised only SWC. The averaged ET/Ep of BS in the whole targeted growth period was 1.16 and 0.83 in SWC-4 and SWC-1, respectively. The ratio of 1.16 in SWC-4 that exceeded 1.00 would have been partly caused by the oasis effect (e.g.,

Table 6. The averaged ET from the soybean pots with the clover mulch (CL) and paper mulch (SP) in each soil water content (SWC) level, and potential evaporation (Ep) calculated by the Eq (1), in each growth stage with those totals in the whole targeted growth period. Different letters beside the values indicated significant differences ($p < .05$) among SWC levels with each mulch by a double-sided t-test of a paired sample with Bonferroni correction.

SWC level ¹⁾	Multi type: CL					Multi type: SP					Ep
	SWC-5	SWC-4	SWC-3	SWC-2	SWC-1	SWC-5	SWC-4	SWC-3	SWC-2	SWC-1	
Stage 1 ²⁾ (mm/d)	1.76 a	1.58 ab	1.48 abc	1.35 bcd	1.29 cde	1.73 a	1.57 ab	0.89 c	0.77 cd	0.58 e	2.85
Stage 2 ²⁾ (mm/d)	3.06 abc	3.10 ab	2.92 abcd	3.20 a	2.64 abcde	2.54 a	2.27 ab	1.69 abc	1.46 abcd	1.17 ade	3.20
Stage 3 ²⁾ (mm/d)	5.89 abc	6.17 ab	6.20 a	5.74 abcd	4.84 bcde	4.70 a	3.87 b	2.55 c	2.12 cd	1.69 de	2.94
Total (mm/d)	3.60 ab	3.64 a	3.57 abc	3.44 abcd	2.94 e	3.02 a	2.59 b	1.71 c	1.45 d	1.15 e	2.32
Total (mm/season)	428.40	433.16	424.83	409.36	349.86	359.38	308.21	203.49	172.55	136.85	276.08

¹⁾ The SWC levels were the same as in Table 1.

²⁾ Stages 1, 2, and 3 were the same as in Table 1.

Table 7. The averaged and the total ET from the soybean pots with the clover mulch (CL) and paper mulch (SP), and evaporation from the bare soil (BS) pots in the soil water content level of SWC-4 and SWC-1. Different letters beside the values indicated significant differences ($p < .05$) among the mulch types, i.e., CL, SP, and BS in each SWC level by a double-sided t-test of a paired sample with Bonferroni correction.

SWC level ¹⁾	SWC-4			SWC-1		
	CL	SP	BS	CL	SP	BS
Stage 1 ²⁾ (mm/d)	1.58 ab	1.57 abc	1.90 a	1.29 a	0.58 bc	1.22 ab
Stage 2 ²⁾ (mm/d)	3.10 a	2.27 abc	2.38 ab	2.64 a	1.17 c	2.17 ab
Stage 3 ²⁾ (mm/d)	6.17 a	3.87 b	3.75 bc	4.84 a	1.69 c	2.43 b
Total (mm/d)	3.64 a	2.59 bc	2.70 b	2.94 a	1.15 c	1.93 b
Total (mm/season)	433.16	308.21	321.30	349.86	136.85	229.67

¹⁾ The SWC levels were the same as in Table 1.

²⁾ Stages 1, 2, and 3 were the same as in Table 1.

Rosenberg *et al.*, 1983) or the advection effect (e.g., Oue and Laban, 2020) in the glasshouse, although the present Ep did not necessarily represent evaporation from open and large water surface but was regarded to represent a reference evaporation under given *St* and *Ta* conditions. The ratio of 0.83 in SWC-1 could be interpreted as that the soil surface evaporation was controlled due to the limited soil moisture in SWC-1. Therefore, ET (evaporation in this case) of BS can be regarded as evaporation that is influenced by the soil moisture condition in each pot and the meteorological conditions in the glasshouse.

In the initial vegetative stage around until the beginning of February (Stage 1), ET/Ep and ET with CL and SP both in SWC-4 and SWC-1 were smaller compared with BS (Fig. 9 and Table 7), except for a little larger ET/Ep and ET with CL in SWC-1. Moreover, SP maintained smaller ET/Ep and ET, while those with CL became larger, compared with BS both in SWC-4 and SWC-1 until the beginning flowering stage of around the middle of March (significantly smaller ET in Stage 2 as shown in Table 7). Also in Stage 3, ET/Ep and ET with SP in SWC-1 was significantly smaller compared with CL and BS, although those in SWC-4 became a little larger compared with BS as shown in Fig. 9 and Table 7, maybe due to the increased transpiration by soybean. Totally in the whole targeted stages, ET/Ep and ET with SP were smaller compared with CL and BS both in SWC-4 and SWC-1 (significantly smallest ET in SWC-1 as shown in Table 7). Meanwhile with CL, ET/Ep in SWC-1 was larger compared with SP and BS in all stages.

The timely increase of ET/Ep shown in Figs. 8 and 9 was caused by the increase of transpiration by the soybean with CL and SP, and additional transpiration by the clover with CL. The larger increase rate of ET/Ep with CL compared with SP and the higher ET/Ep even in SWC-1 with CL than in SWC-4 with SP, would have been caused by the increased transpiration by the growth of the interseeded clover shown in Fig. 7.

With SP, the largest ET in SWC-5 in all growth stages (Table 6) meant that the soybean consumed largest amount of water without producing largest LAI and DM (Table 4 and Fig. 8). With CL, on the other hand, the largest ET, not in SWC-5 but in the drier conditions such as SWC-2 in Stage 2 (Table 6), would have been mainly due to the offset effect of smaller transpiration by the clover in SWC-5 with the poorer growth in the excessive wet condition (Fig. 7 and Table 5), while the relatively larger soybean plant in SWC-5 compared with the drier conditions (Figs. 4 and 5, and Tables 3 and 4) should have had larger transpiration. The ET with CL that was not very significant between each SWC level suggested the interseeded clover consumed quite amount of water even under the lower SWC, which would have been supported by the better growth of the clover in SWC-1, SWC-2, and SWC-3 compared with SWC-4 and SWC-5, as stated above and shown in Table 5 and Fig. 7.

In the initial vegetative stage, i.e., Stage 1, smaller ET and ET/Ep both with CL and SP in SWC-4, and with SP also in SWC-1 (Fig. 9 and Table 7) compared with BS suggested that both the shredded paper and the clover as a cover crop in this growth stage could have functioned to save soil surface evaporation. After Stage 1 or through the whole targeted growth period, however, the smaller or a little larger but quite similar (just in

SWC-4 in Stage 3) ET and ET/Ep with SP compared with BS, and larger ET and ET/Ep with CL compared with BS both in SWC-4 and SWC-1 demonstrated clear contrast between the two types of mulch. The shredded paper mulch well contributed to conserve soil moisture by saving soil surface evaporation especially under the dryer soil moisture condition, while the clover living mulch did not function to conserve soil moisture due to the consumptive water use by the clover even in SWC-1.

3.5. Water use efficiency in each treatment

Water use efficiencies for (a) the total aboveground DM (WUE_{total}) and for (b) the seed (WUE_{seed}) with CL and SP in each SWC level were shown in Fig. 10 with the statistical significance ($p < .05$) between SWC levels for the individual mulch type by a double-sided t-test for two samples of non-homovariances with Bonferroni correction. The statistical significance between CL and SP in each SWC level was also analyzed but not shown in Fig. 10. In all SWC levels, both WUE_{total} and WUE_{seed} were higher with SP compared with CL. The difference in WUE_{total} between CL and SP was significant in all SWC levels. The difference in WUE_{seed} between CL and SP was significant except for SWC-2 and SWC-5. With CL, both WUE_{total} and WUE_{seed} were highest in SWC-5, while lowest in SWC-1. With SP, on the other hand, both WUE_{total} and WUE_{seed} were higher in the lower SWC. The higher WUE_{total} and WUE_{seed} in all SWC levels with SP compared with CL were caused by a synergistic effect of smaller ET and better growth of the soybean in SP.

With CL, WUE_{total} and WUE_{seed} were highest in SWC-5 among the five SWC levels. The reason especially for the highest WUE_{total} was the larger total aboveground DM in SWC-5 compared with the other SWC levels (partly with significance) as shown in Fig. 6, while the difference in ET was not very significant between the SWC levels (Table 6). This suggested that cultivation with CL was very water consumptive. Meanwhile, with SP, WUE_{total} and WUE_{seed} were highest in SWC-1 among the five SWC levels. The reason was the smallest ET with SP in SWC-1 mostly with significance compared with the other SWC levels (Table 6), while both DMs were not significantly different between SWC levels (Fig. 6) as specified in 3.3. This suggested the high applicability of shredded paper to the water saving cropping system.

4. Conclusions

The growth, biomass production, actual evapotranspiration (ET), and water use efficiency (WUE) of soybean were different in the five soil water content (SWC) levels and between the two mulches, i.e., white clover living mulch (CL) and shredded paper mulch (SP).

In terms of plant height, LAI, and above-ground dry matter (DM) in CL and SP pots, the soybean grew better with SP especially in the moderate SWC, i.e., SWC-3 and SWC-4, and worse with CL especially in the lowest SWC-1. The clover, applied as an interseeded living mulch to the CL pots, grew better than the soybean in the lower SWC, i.e., SWC-1 and SWC-2. This study demonstrated a possibility that the soybean with CL in the lower SWC suffered from the negative synergistic effect of water stress and competitive water use with the clover.

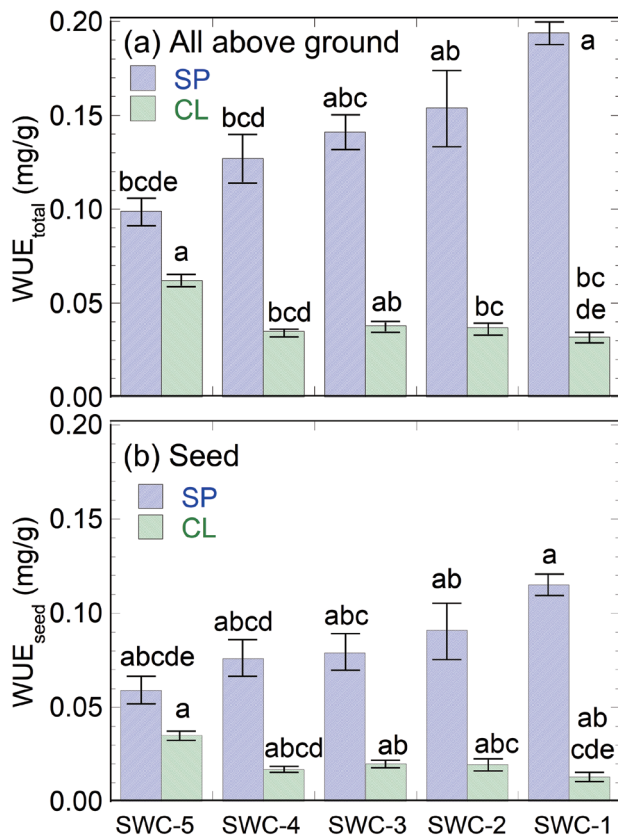


Fig. 10. Comparisons of water use efficiencies of the soybean for (a) the total dry matter (WUE_{total}) and for (b) the seed (WUE_{seed}) with CL and SP in each SWC level. The standard error was shown by the vertical line on each bar graph. Different letters above the bars indicate significant differences ($p < .05$) between SWC levels for the individual mulch type by a double-sided t-test for two samples of non-homovariances with Bonferroni correction.

The measured ET was significantly larger with CL compared with SP mostly in all SWC levels, e.g., the average ET in the whole period was 2.59 and 3.64 (mm/d) under the second wettest SWC level, i.e., SWC-4 (33.6% and 33.4% in average) in SP and CL, respectively. The smaller ET/Ep with SP and larger ET/Ep with CL compared with bare soil (BS) demonstrated that SP well contributed to conserve soil moisture by saving soil surface evaporation especially in the lower SWC, while the clover in the CL pots required larger irrigation rate by consuming more soil moisture by soil surface evaporation and additional transpiration by clover even in the lowest SWC.

The highest WUE for seed was obtained with SP in the lowest SWC (0.115 mg/g), while WUE for seed with CL was highest in the highest SWC (0.035 mg/g), which was lower compared with SP. If production would be prioritized and agricultural water would not be so limited, SP in wetter soil moisture condition, not in fully saturated, could be evaluated as the best treatment.

This study suggested that shredded paper mulch was effective for water saving cropping system with larger WUE compared with clover living mulch by a synergistic effect of the better growth of the soybean and the smaller ET.

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Author contributions

H.O., Conceptualization, Supervision, Data curation, Investigation, Methodology, Validation, Visualization, Formal Analysis, Writing-original Draft, and Writing-review & editing; M.M.M., Conceptualization, Data curation, Investigation, Methodology, and Writing-review & editing; Y.Z., Investigation and Writing-review & editing.

Data availability

Data will be made available upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval and consent to participate

All authors approved their participation in this research.

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