Effectiveness of various types of mulching on soil moisture and temperature regimes under rainfed soybean cultivation

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CHAPTER 1

General introduction

1.1 Background

Rapid increase of the world population, pollution of natural resources, global warming and climate change are putting increasing pressure on limited water resources (Colak et al., 2015; World Water Assessment Programme, 2012). Agriculture is the largest water consumer in the world that accounts 70% of total use (Qin et al., 2018). Approximately 80% of worldwide cropland is rainfed (non-irrigated) that produces 60–70% of the world food (Chen et al., 2018). Considering the growing water shortage, rainfed crop cultivation plays a prime role in the worldwide food supply (Li et al., 2017; Sun et al., 2012). Thus, agricultural water management is a major concern to save water in cultivated land. Therefore, conservative and efficient water use has been practiced for many years in arid and semi-arid regions of the world with a great success. The goal of all the water conservation systems is to maximize yield by minimizing water use. Therefore, conservation of water by using appropriate soil management practices may be an efficient option to save water as well as raising production in rainfed farming.

Mulch is a coating material spread over the soil surface (Kasirajan and Ngouajio, 2012) for controlling soil hydrothermal environment and microclimate modifications (Kader et al., 2017). It insulates soil to protect organisms and plant roots from different meteorological conditions. The interactions between mulching practices and global climatic environments are illustrated in **Fig. 1.1**. Mulching technique establishes a linkage between soil and agrometeorology, which can modify the crop growing environment (**Fig. 1.1**). Two types of mulches are is use: organic mulch made of organic materials and inorganic mulch mainly made of plastic-based materials (Kader et al., 2017). Organic and plastic materials are used as mulch based on their purposes while selection of best one is still in contradictions by considering profitability and environmental aspect. Now, it is important to know the effectiveness of mulching, which is useful and essential for soil conservation practices in the rainfed areas. Contradictory effects of mulching on soil moisture and temperature due to varying climatic conditions (rainfall and temperature), mulch material types, soil energy behaviors, soil characteristics and crop types have been reported (Haapala et al., 2015; Zhang et al., 2009). One the other hand, the use of plastic film is becoming popular in agriculture to control soil temperature and increase water use efficiency. The application method of plastic film is mostly followed by flat layout, ridge-furrow, raised bed with various film thickness. The new modifications of plastic film application method may have a potential to optimize the performance of film mulching to increase the water use efficiency. For example, non-perforated plastic mulching reduces adequate rainfall by preventing infiltration of rainwater, while perforated plastic (plastic-hole) mulch can increase effective rainfall by enhancing infiltration. Moreover, the selection criteria of organic mulch depend on local availability of materials. For example, south-Asian farmers use mainly rice straw mulch because of being higher rice production zone it can supply enough straw. Small homestead gardener uses craft paper, wood product and newspaper as mulch materials. Therefore, the effects of both organic and plastic mulching on soil environments need to be

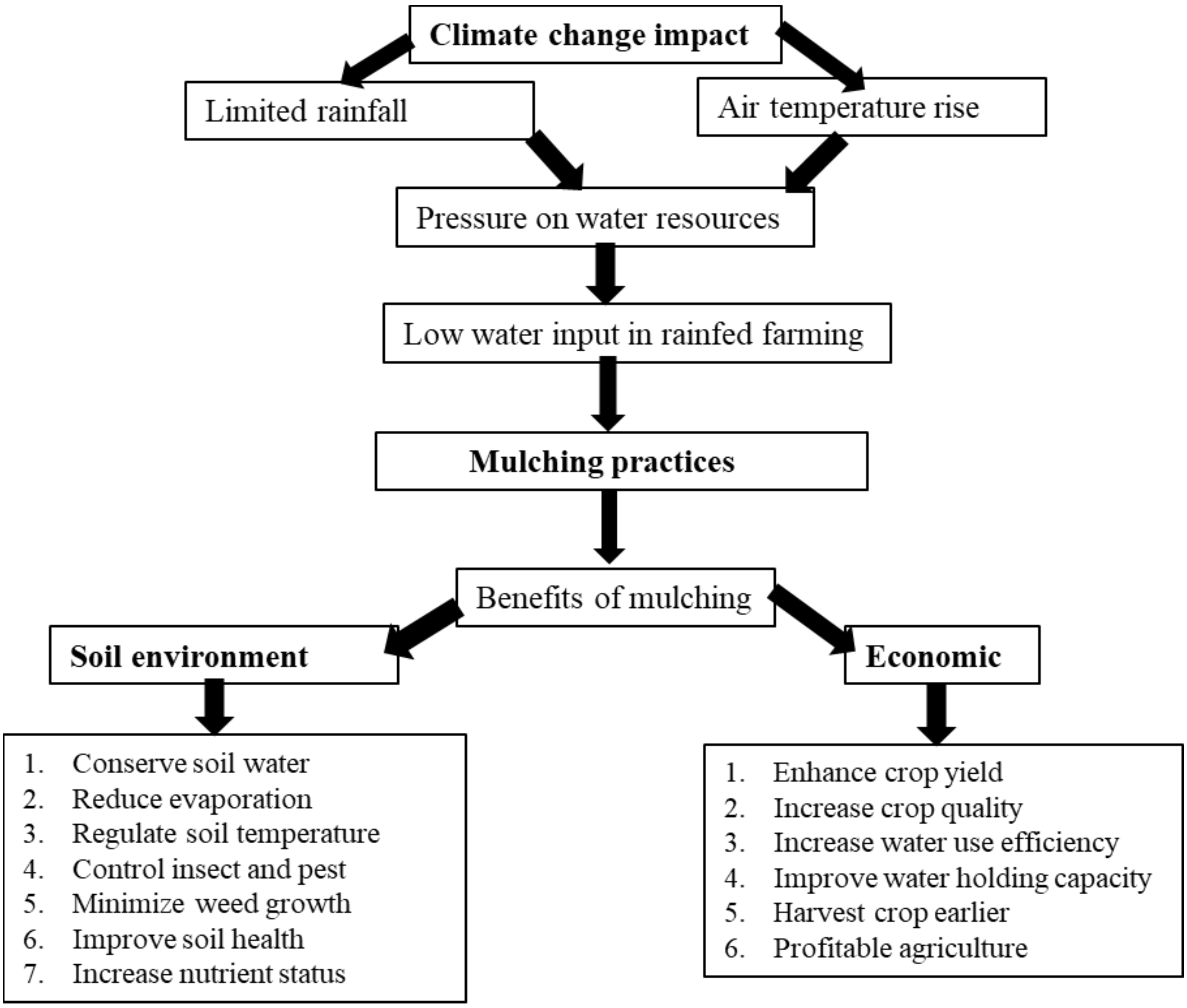

Figure 1.1 Schematic diagram of the interaction mulching practices and climate change.

investigated under different crops and climates. This efficiency knowledge of different types of mulch can provide a clear idea to select the right mulch in a suitable crop for modifying soil hydrothermal regimes.

Soybean is an economically important agricultural crop across the world (FAOSTAT, 2016). Its growing environment has been considered suitable in Japan for many years (Uchino et al., 2016). Soybean is used as a source of oil seed in most countries (Saberali and Mohammadi, 2015); but in Japan, it used as a source of protein (Kokobun, 1991) and fodder crops in recent years (Uchino et al., 2016). In addition, soybean crop is globally important for sources of food, feed and energy (bio-diesel) which contributes to 25% of the global edible oil. In Japan, it is specifically popular in cookery as vegetable cuisine, soymilk, tofu, miso and yoghurts (Matsuo et al., 2018). However, soybean is a vital non-irrigated (rainfed) crop of converted fields in Japan that have excess soil moisture during the rainy season and influences the growth in early vegetative stages (Kato et al., 2019). Besides, the cultivation of soybean is decreasing over the year in Japan due to easy import and land converted to other crops. Gifu

Prefecture is one of the soybean production areas in Japan, although Hokkaido and Miyagi Prefectures are the most productive regions for the crop (MOAFF, 2018; Konovsky et al., 1994). Suitable environment with optimum root zone moisture and temperature are needed for the production of superior quality with higher yields of soybean crops. During the hot summer days (July–August), high soil temperature accelerates evaporation and reduces soil moisture content, with a consequent negative impact on the growth and development of the crop. In central Japan area, air temperature rises up to 34°C in the hot-dry months during July to August. Mean annual rainfall in the area is 1800 mm, 34% of which occurs during June through August, with the highest rainfall (13.7%) in July. For satisfactory yield, cultivation of soybean in rainfed condition needs to modify soil hydrothermal regimes. The appropriate mulching materials, by controlling soil temperature and conserving soil moisture can provide suitable microclimate for soybean cultivation. Therefore, it is essential to know the effectiveness of various types of mulch materials on soil hydrothermal regimes under rainfed soybean cultivation in central Japan areas.

1.2 Research problems

Saving of agricultural water in rainfed crop cultivation is crucial to reduce pressure on limited water resources. Soil mulching may be necessary in agriculture to conserve water particularly in areas with lower rainfall and higher evaporation demand. Soybean is a high nutrient value crop cultivated after rice and wheat crops in Japan. With rising demand of soybean in Japan, domestic production is affected by diversification of crop rotation and meteorological disasters. Therefore, domestic production of soybean crop needs to be increased by adopting various crop management strategies, including soil and water converation practices. In rainfed fields, soybean cultivation using various mulching may have significance in increasing water and crop productivity. However, the characteristics of various mulch materials and their application methods for water conservation and microclimate modification needs to be identified by considering the effective water use strategies in rainfed crops. Likewise, production of soybean under limited rainfall is a great challenge since the crop is highly sensitive to rainfall and temperature that needs be controlled by applying various types of mulching to achieve maximum production of soybean. Many researchers have been developing new types of mulching materials like paper-based materials, sprayable polymer film, geo-textile, and bio-based and compostable plastics that might be important in future research for long-term interaction between soil and water environment. Organic mulch may derive from decomposable materials like crop straw, wood products, residues, and animal wastes. The effectivity of that organic mulching may need to evaluate for different crops. The future research is therefore needed to investigate the effects of newly developed mulching on crop growth, microclimate modifications, and crop yields. Moreover, farmers can use plastic film with ridge-furrow technique to harvest rainwater where rainfall is limited. Also, flat plastic application method restricts the entry of rainwater while a limited amount of water infiltrated through the planting holes.

Therefore, the design of new mulching pattern (plastic-hole) over traditional flat plastic film and use of newspaper as mulch materials in agriculture that is rarely used by farmers and has not been investigated yet. Moreover, the color of the plastic film is a vital aspect when selecting the mulching since it can regulate thermal regime of a soil. However, the effects of plastic mulching vary with rainfall, soil types, and soil moisture content, but color of the plastic film may alter heat budget to modify soil temperature (Fan et al., 2017) and can affect crop growth by controlling growth of roots and foliage (Gan et al., 2013). Therefore, further research on colors of plastic film is necessary to investigate the effects of plastic mulching (Mahadeen, 2014). Although, many natural factors (e.g., weather, crop and climatic regions) affect the effectiveness of mulching, the color(s) of plastic film that may be suitable in our study area has not been studied yet.

In this thesis, we solve a few interesting problems on various types of mulching materials and their effectiveness on soil environments in a rainfed soybean field. Specifically, we evaluated the effects

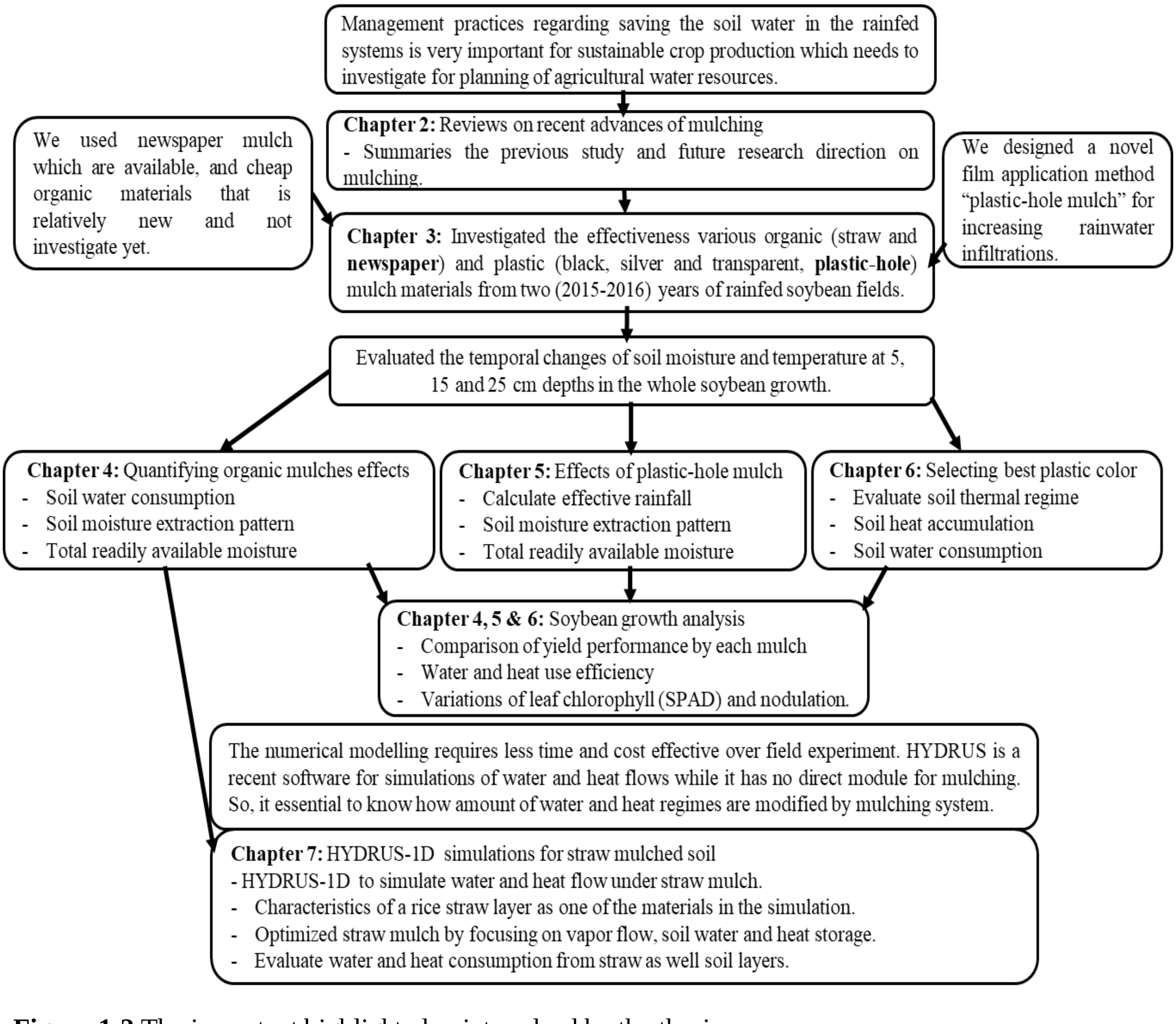

Figure 1.2 The important highlighted points solved by the thesis.

of various mulching materials on soil moisture and temperature regimes at different soil layers in a rainfed soybean crop of central Japan area. Furthermore, the growth and yield attributes of soybean crops were analyzed under both organic and plastic mulching treatments. The key highlighted original points of this thesis have been illustrated in **Fig. 1.2**.

Simulations of numerical modeling can be used as a tool for assessing various mulching techniques in terms of the effects on soil water and heat dynamics and changes in soil physical environments. Moreover, there is a limited number of researches that address the modeling effects of organic and plastic mulching on soil moisture and temperature under various management practices. Numerical simulation approach is an effective way to find field soil hydraulic parameters because field experiments are expensive and requires much time. Hence, these models can be used to estimate soil water balance components and water productivity under different land management and irrigation planting methods. Moreover, various irrigation planning strategies can be evaluated by quantifying water use efficiency and how the amount of water-saving by different mulching. HYDRUS (Šimůnek et al., 2008) is one of most widely used softwares in soil hydrothermal model for simulating water, nutrient and heat movement in one, two and three dimensional variably saturated porous media. There is no direct code in HYDRUS model for simulations of mulch covering soil, which is difficult due to different characters of mulch materials with varying thickness. Therefore, numerical simulations studies can be applied in various mulched soil to understand the water and heat flow behaviors and quantify the efficiency of mulch materials for modifying soil environment.

1.3 Research objectives

The overall objectives of the study are to summarize effectiveness of various mulching materials on soil moisture and temperature regimes and their effects on water and crop productivity of rainfed soybean cultivation. Specific objectives of the study are as follows:

1. To evaluate the effects of straw and newspaper mulching materials on soil hydrothermal regimes (soil moisture and temperature, soil water consumption and its distribution in crop root zone), which affect growth, yield and water use efficiency of rainfed soybean cultivations.
2. To evaluate and compare the effective rainfall, total readily available soil moisture and soil moisture extraction pattern of the two (plastic, plastic-hole) mulching and bare soil treatments under soybean cultivation.
3. To investigate the comparative effects of three popular colors (black, silver and transparent) of plastic film mulches and a bare soil control (no mulch) on soil temperature and soil water consumption along with their impacts on growth, yield and water productivity of rainfed soybean.

4. To simulate water and heat flow regimes by HYDRUS-1D (Šimůnek et al., 1998) under rice straw mulching and bare soil in order to analyze water consumption, ratio of vapor to total water transport, water balance and heat storage in the root zone in the field soil of rainfed soybean field.

1.4 Outline of the thesis

This thesis consists of eight chapters including the four major chapters and general introduction, review of literature, methodology and summaries. The overall outline of each chapter of the thesis is illustrated in **Fig. 1.2**. Moreover, the structure and content of each chapter is discussed as follows.

Chapter 1 shows the general introduction of the thesis where the background of the study, research problems and objectives of the thesis were discussed step by step. Also, the prospects and key challenges of the research have been analyzed in this chapter by highlighting the originality of the study.

Chapter 2 is a review of literature on mulching materials and its effect on soil hydrothermal regimes in arid and semi-arid environments. This chapter has reviewed a large number of published research papers, which described the effects of various mulching materials and methods on soil environment that influences on crop productivity especially soybean. A brief comparison between organic and inorganic (plastic) mulching and their effects of soybean cultivations in central Japan area is focused on. It provides a discussion about soil mulching and its advantages over soil environment by summarizing recent articles. Besides, the importance of numerical simulation of different mulching techniques is discussed. Finally, two important phenomena of soil physics (soil moisture and temperature) and its coupling flows on soil environments were discussed.

Chapter 3 is the general material and methods of the field experiments. The essential information of study site, treatments, field set up, sensor orientations, soil sample collection procedures and analysis of the experiments are enumerated in this chapter. Moreover, measurement procedure of various soil and water parameters in the field experiments were illustrated. Finally, the methodology of water and heat use efficiency and consumption to quantify various mulching effects were discussed.

Chapter 4 includes the effects of rice straw and newspaper mulching materials on soil hydrothermal regimes, growth and yield of rainfed soybean yield. Quantifications of straw and newspaper mulching by analyzing soil moisture and temperature, soil water consumption, water extraction pattern and total readily available water in the soil root zone, which affects the yield and water use efficiency of soybean.

Chapter 5 discusses the comparative performance of plastic-hole mulch with plastic and bare soil treatments on effective rainfall and available soil moisture utilization. This chapter evaluated the effective rainfall of plastic-hole mulching by analyzing the total readily available soil moisture (*TRAM*), soil moisture extraction pattern (*SMEP*) and finally compared yield performance of soybean in contrast to plastic and bare soil.

Chapter 6 compares the effects of soil thermal regime under various colors (black, silver, transparent) of plastic film with bare soil on growth and productivity of rainfed soybean. Soil temperature effects of various plastic colors were summarized from a field experiment. Finally, a suitable plastic colour for soybean production in central Japan area was recommended.

Chapter 7 performs the numerical simulations of water and heat flow regimes of straw mulched soil using one-dimensional HYDRUS software package. This chapter focuses on the effects of straw as a layer material of mulch on the soil surface and investigates the coupled of vapor, water and heat flow characteristics of straw materials.

Chapter 8 provides the overall discussion and concludes remarks of the thesis by including major findings of individual chapter. This chapter also provides the general conclusion and future research directions of present study.

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CHAPTER 2

Recent advances in mulching materials and methods: review

2.1 Mulch

The English word 'mulch' is derived from the German word "molsch", which means soft or beginning to decay (Jacks et al., 1955). Mulches are defined as materials that are applied to soil surface, as opposed to materials that are incorporated into the soil profile (Chalker-Scott, 2007). Mulch is a layer of material(s) that covers the soil surface, and mulching is a water conservation technique that increases water infiltration into the soil, retards soil erosion and reduces surface runoff (Adekalu et al., 2007; Ghawi and Battikhi, 1986). Mulching is an effective method of manipulating the crop growing environment to increase crop yield and improve product quality by controlling soil temperature, retaining soil moisture and reducing soil evaporation (Chakraborty et al., 2008).

2.2 Mulching materials and methods

The mulching materials are broadly classified into three main groups: organic materials (e.g., plant products, animal wastes), inorganic materials (synthetic materials) and special materials (**Table 2.1**). The organic mulching materials are derived from organic substances such as agricultural wastes (straw, stalks), wood industrial wastes (sawdust), processing residues (rice husks) and animal wastes (manure). The inorganic mulching materials include polyethylene plastic films, which are petroleum based products (Gill, 2014), and synthetic polymers (Kyrikou and Briassoulis, 2007). There are also other types of organic and inorganic mulching materials (SSSA, 2007; Mbah et al., 2010). Adhikari et al. (2016) and Yang et al. (2015) described several new types of biodegradable and photodegradable plastic films as ecological materials, and proposed sprayable and biodegradable polymer films for easy application and versatility. Some easily available special materials, such as sand and concrete, have also been used for mulching, but very rarely, due to some inherent disadvantages of the materials; for example, sand mulching reduces soil nutrients (Gan et al., 2008) and concrete mulching is very

Table 2.1 Different classes of mulching materials.

Organic materials	Inorganic materials	Special type materials
straw (rice, wheat, maize)	biennial color plastic film	gravel (sand–gravel)
dry clips (grass, weeds, wood, bark)	black plastic film	concrete
chopped leaves, cassava bagasse	silver plastic film	tephra mulch
geo-textile materials	transparent plastic film	hydro mulch
husks (rice, coconut, maize stalk)	plastic film with holes	
small branches of tree	biodegradable plastic film	
paper (newspaper, kraft paper)	photodegradable plastic film	
animal wastes (cow dung, manure)	spray able polymer film	
cover crops (weed, fodder)		

expensive to construct (Lei et al., 2004). Each type of mulching material has a particular set of characteristics. The choice of selection of an appropriate mulching material depends on local climate, cost-effectiveness (Wang et al., 2015) and feasibility for the crop. Now-a-days, researchers are exploring new types of mulching materials. So, comprehensive field trials are crucial with various mulching materials on a continuous basis to identify efficiency and cost-effectiveness of the new mulching materials.

Various mulching materials are applied in agricultural field by different methods and in different patterns as illustrated schematically in **Fig. 2.1**. 'Flat mulching' is a traditional method of mulch application in which soil surface is covered by organic, inorganic or mixed mulching materials (**Fig. 2.1** a & b) (Ghosh et al., 2006; Sun et al., 2012). In case of organic mulching materials, flat mulching can maintain various thicknesses according to the intended purpose. 'Plastic mulching with holes' is a modified flat mulching (**Fig. 2.1**b) in which soil surface is only partially covered. This mulching increases rainfall infiltration and soil aeration compared to the traditional flat mulching (Li et al., 2003; Kader et al., 2017). 'Ridge shape mulching' has been popularly used in loess plateau area of China for harvesting rainwater (Tian et al., 2003). In this type of mulching, the ridge is covered by plastic film that channels rainwater into furrows and minimizes surface runoff (Gan et al., 2013) and, consequently, increases water use efficiency (Zegada-Lizarazu and Berliner, 2011). Generally, crops like corn are planted on the ridge part covered with mulching materials (Zhao et al., 2014), but, sometimes, crops are also planted in the furrow part either with mulching (**Fig. 2.1**d) or without mulching (**Fig. 2.1**c). 'Ridge-furrow mulching' is a full mulching on both ridges and furrows by plastic film (Zhao et al., 2014) or together organic mulches with plastic layers (Yin et al., 2016); crops are planted either on the ridge or in the furrow or on both (**Fig. 2.1**d). It has been found more effective in harvesting rain water and reducing soil surface evaporation rate compared to the conventional flat mulching (Li et al., 2006; Wang et al., 2009). Gan et al. (2013) briefly explained ridge-furrow mulching system in semi-arid environment for increasing crop water availability, improving soil productivity and boosting environmental benefits. Yin et al. (2016) reported a double mulching system established by plastic film coupled with straw mulch (plastic film on straw in the maize strips) for intercropping of wheat and maize production in northwestern China (**Fig. 2.1**d). The effects of various mulching patterns on water conservation through rainwater harvesting for corn, wheat and mixed cultivation practices have been reported in several recent studies (e.g., Ren et al., 2016; Wang et al., 2016).

2.3 Application of mulching materials

Mulching practices in the agricultural field have a number of advantages. They protect the soil from physical, chemical and biological degradation, and reduce irrigation requirement by conserving water. Many investigators studied the application of mulching materials on various target crops (**Table 2.2**).

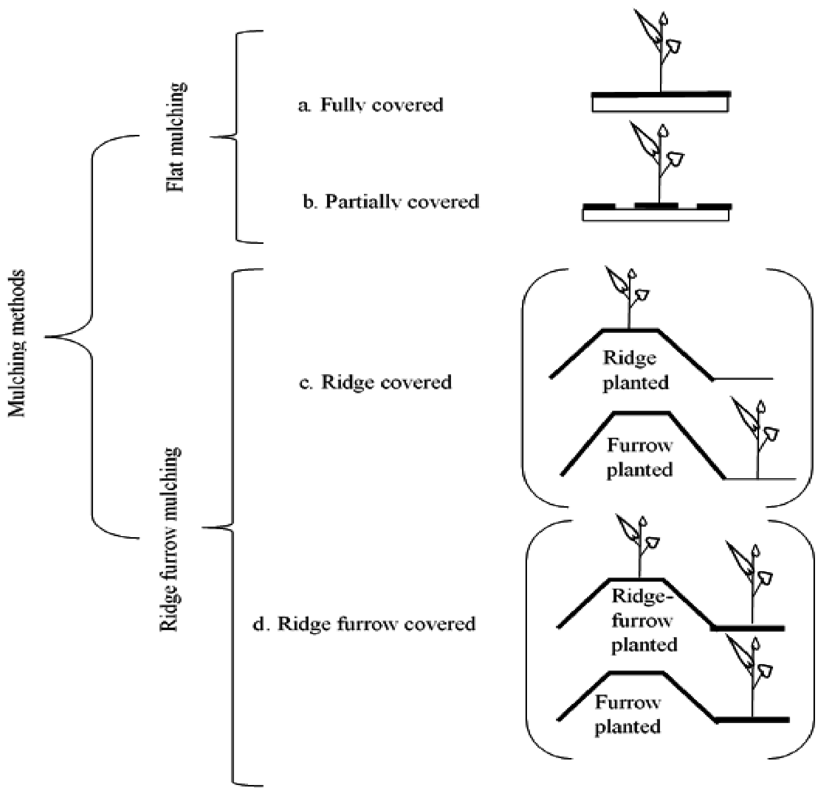

Figure 2.1 A schematic diagram of different mulching methods (▬ line indicates cover by mulch materials).

The popular organic mulching materials, such as straw and grass, were applied to increase soil moisture availability by reducing soil evaporation and maintain soil temperature in order to increase crop production. Almost all the organic mulching materials were applied under flat type mulching (**Fig. 2.1**a) in order to investigate mulching time, mulch application rate, soil microbial activity and crop yield.

2.3.1 Organic mulching

Cereal straw is a most common organic mulching material in almost all climatic areas that has several benefits after applying in the field and is suitable for soil moisture storage (Ji and Unger, 2001). Application of straw mulching at 4 to 6 t ha^{-1} has been found effective in improving soil physical condition, including protection of the topsoil, in tropical environments (Lal, 1974). In the study of Mutetwa and Mtaita (2014), trash grass mulching favored the growth of onions more than sawdust mulching. Dixit and Majumdar (1995) obtained 27.9% increase of potato yield with 18.2% increase in starch content under straw mulching compared to the non-mulched plot. Under temperate environments, straw mulching has been reported to intercept 44% of the total rainfall at a typical rate of 2.6 mm day^{-1} (Price et al., 1998). The organic mulching reduced direct evaporation from the wet soil surface (Agassi et al., 2004; Ji and Unger, 2001).

Table 2.2 Research works done on different mulching materials under various crops.

Mulching			Crop	References
Types	Materials	*		
organic	straw	1	tomato	Tu et al. (2006); Lal (1974)
	grass	1	yam	Olasantan (1999)
	straw, grass, leaf debris	1	-	McMillen (2013); Price et al., (1998)
	straw, maize	1	maize	Cai et al. (2015)
	wheat straw	1	soybean	Siczek et al. (2015); Sekhon et al. (2005)
	wheat straw	1	-	Jordán et al. (2010); Ji and Unger, (2001)
	rice straw, compost	1	wheat	Balwinder-Singh et al. (2011); Agassi et al. (2004)
	trash grass, sawdust	1	onion	Mutetwa and Mtaita (2014)
	straw (soybean, wheat)	1	maize	Cook et al. (2006)
	paper	1	squash	Coolong (2010)
	straw	1	potato	Döring et al. (2005); Dixit and Majumdar (1995)
	cover crop (weed)	1	soybean	Moore et al. (1994)
inorganic	plastic film	3, 1	maize, lettuce	Xiukang et al. (2015); Almeida et al. (2015)
	plastic film	4	corn, vegetables	Ren et al. (2016); Filipović et al. (2016)
	plastic film	4	potato, cotton	Zhao et al. (2014); Dong et al. (2009)
	black, silver, clear plastic	1	Peanut	Sun et al. (2015); Ibarra et al. (2012)
	narrow and wide plastic	1	broccoli, wheat	Zhang et al. (2015)
	plastic and biodegradable	1	tomato, cabbage	Moreno and Moreno (2008); Tiwari et al. (2003)
mixed	plastic, straw, concrete	1	jujube	Sun et al. (2012)
	plastic, straw, grass	4	peach	Wang et al. (2015); Opara-Nadi (1993)
	plastic, straw, gravel	1	maize	Liu et al. (2015); Li et al. (2013)
	wheat straw, black plastic	1	groundnut	Ghosh et al. (2006)
	rice straw, clear plastic	1	groundnut	Ramakrishna et al. (2006)
	straw, plastic, geo-textiles	1	-	Zribi et al. (2015)
	plastic	1	chilly	Asharafuzzaman et al. (2011)
special	gravel	2	-	Yuan et al. (2009)
	tephra	1	-	Diaz et al. (2005)
	concrete	1	jujube	Lei et al. (2004)

*(Position in **Fig. 2.1**); 1: Flat mulch, 2: Flat mulch with hole, 3: Ridge pattern, 4: Ridge–furrow pattern.

2.3.2 Inorganic mulching

The application of plastic mulching in agriculture, called plasticulture, has increased dramatically throughout the world since 2000 (Kyrikou and Briassoulis, 2007). Plastic is now used in all types of climate, seasons and soils for its numerous benefits, in addition to enhancing soil temperature (Kasirajan and Ngouajio, 2012). Various inorganic mulching materials (**Table 2.2**) were applied under different methods such as flat, ridge or ridge-furrow (**Fig. 2.1**) and tried with different plastic colors and thicknesses. In various studies (**Table 2.2**), plastic mulches were found to enhance soil moisture retention (Ghosh et al., 2006) and accelerate crop growth with increased yield (Tiwari et al., 2003). Most of the inorganic mulching researches, done in the Chinese loess plateau area, described the effects of rainfall on soil moisture storage under various crop productions. Other works in other regions and countries focused on the effects of mulching on soil water environment as well as on water use efficiency (Almeida et al., 2015; Ibarra et al., 2012; Filipović et al., 2016). The plastic mulching was found very effective for reducing soil evaporation, improving crop water use efficiency (Almeida et al., 2015) and minimizing salt build-up in the crop root zone (Dong et al., 2009; Yuan et al., 2009). As the short-term effects on soil conditions (control on temperature and moisture), the plastic mulching provides higher product yield and quality, and, consequently, higher economic value for farmers (López-López et al., 2015). But, the long term effects on soil quality, farm profitability, environmental pollution and ecosystem services need to be considered on public awareness and farmers' perceptions (Steinmetz et al., 2016). So, the use of plastic mulching materials may be a prospective and potential water conservation practice in the contemporary agriculture.

2.3.3 Mixed mulching

The mixed applications of organic and inorganic materials as mulching treatments were also practiced under various crop conditions in different climatic zones (**Table 2.2**). Luo et al. (2015) studied the effects of gravel and plastic film mulching on soil organic carbon in semi-arid climate in order to enhance crop productivity and maintain soil quality. Abouziena and Radwan (2015) and Dong et al. (2009) described mulching the soil with plant wastes or synthetic plastic as one of the best management practices to control soil evaporation, improve soil moisture retention and increase water use efficiency. Thus, mulches improved the soil environment for optimum crop growth and yield (Opara-Nadi, 1993). The prospective future studies, therefore, need to address new applications of mulching practice in different soil and climatic conditions under various crop management practices.

2.4 Effects of mulching materials

2.4.1. Soil moisture

Soil moisture information can be used for reservoir management, early warning of droughts, irrigation scheduling, and crop yield forecasting. The effects of mulching on soil moisture depend on precipitation and climatic factors. Mulching favorably influences soil moisture regime by controlling surface evaporation rate; in summer, mulching conserves soil moisture by reducing the evaporation rate. Mulches improve soil moisture retention capacity as well as soil structure and suppress weed growth (Mutetwa and Mtaita, 2014). The amount of soil moisture conservation under different mulching materials differs in different soil types and climatic conditions. In general, the mulching treatments store higher soil moisture compared to the bare soil (no mulch) (Chakraborty et al., 2008; Zhao et al., 2014). The changes of soil moisture in the upper surface layer (0–10 cm) are highly dynamic due to water vapor fluxes across the soil-atmospheric interface (Bittelli et al., 2008). However, mulching reduces the fluctuation of soil moisture and soil temperature (Abouziena and Radwan, 2015). Rainfall directly infiltrated into the soil surface of the bare treatment, while the other treatments of mulch cover prevented direct infiltration. Paper mulching provided the highest soil moisture by the reason that paper is inherently porous and hygroscopic, and it expands and shrinks with the change in its moisture content (Daene, 2005; Haapala et al., 2014). By comparing the effects of various mulching materials with bare soil treatment under maize, soybean and tomato cultivation in the USA, Munn (1992) reported obtaining cooler soil temperature and higher soil moisture content under newspaper mulching. In contrast, for lettuce crop cultivation during dry period, Jenni et al. (2004) found plastic film as more effective to conserve soil moisture than paper mulch. Also, as reported by McMillen (2013), the application of mulch with wheat straw, grass clippings and leaf debris of 5 to 10 cm depth increased soil moisture by 10% compared to the bare soil. Rainfall directly infiltrates into the soil surface of the bare treatment, while the other treatments of mulch cover prevent direct infiltration.

Mulching has a positive impact on soil moisture storage that depends on the type of mulching materials and thickness of mulching. The ability of plastic mulch to conserve soil moisture is greater than organic mulches (Chakraborty and Sadhu, 1994). Plastic mulch treatment stored the highest amount of soil moisture compared to the organic mulch treatments, which stored greater moisture than the bare soil (Ogundare et al., 2015). Contrasting results were also reported in regard to soil moisture storage under different mulching materials. Khan et al. (1988) found mulching with rice straw to be more effective than plastic mulch, while Begum et al. (2001) reported obtaining the highest soil moisture storage with straw mulch among different mulch treatments. **Table 2.3** illustrates the various effects of mulching on soil and water environments.

Compost mulching reduces surface runoff during and after rainfall, increases infiltration and reduces soil loss (Bakr et al., 2015). Jordan et al. (2010) also reported similar results from a 3-year experiment on application of straw mulch under cultivated soils in semi-arid environment. Ashrafuzzaman et al. (2011), on the other hand, did not find significantly different soil moisture contents among the various mulch treatments; but they always obtained greater soil moisture content under mulch treatments than the bare soil. In the experiments of Ashrafuzzaman et al. (2011), transparent plastic mulch provided the highest soil moisture (21.1%), followed by black plastic mulch (20.4%) and blue plastic mulch (19.2%), and the control (bare soil) (14.6%) provided the lowest soil moisture at 0–10 cm soil profile at 90 days after transplanting of Chilli pepper (Capsicum annuum L.). Besides moderating soil moisture and temperature, mulch residue also affects the dynamics of soil organic matter (Huang et al., 2008) that can augment dissolved organic carbon (C) and nitrogen (N) by decomposition of plant materials (Chantigny, 2003).

Table 2.3 Effects of mulching on soil and water environment.

Parameter	Indicator	References
soil environment	soil moisture	Montenegro et al. (2013); Gicheru et al. (2005); Lal (1974); Xiukang et al. (2015)
	soil temperature	Herbert (1964); Ramakrishna et al. (2006); Lamont (1993, 2005); Sinkevičienė et al. (2009); Zhang et al. (2009); Pramanik et al. (2015)
	water use efficiency	Qin et al. (2015); Xu et al. (2015b); Mahajan et al. (2007); Wang et al. (2015); Yin et al. (2016)
	infiltration	Adekalu et al. (2007); Bakr et al. (2015)
	runoff control	Findeling et al. (2003); Atreya et al. (2008)
soil microbiology	soil microbial activity	Jacometti et al. (2007); Huang et al. (2008)
	soil enzyme	Zhang et al. (2015)
	earthworm population	Tian et al. (1997); Ortiz-Ceballos and Fragoso (2004)
	N mineralization	Cabrera et al. (2005)
	soil borne diseases	Abawi and Widmer (2000)
	soil micro fauna	Forge et.al. (2003)
	soil biodiversity	Lin et al. (2008)
	soil solarization	Komariah et al. (2011)
soil properties	soil quality and productivity	Mulumba and Lal (2008); Lumbanraja et al. (2004)
	soil aggregates and density	Tindall et al. (1991)
	soil erosion	Gyssels et al. (2005); Smets et al. (2008); Afandi et al. (2003)
	electrical conductivity, pH	Kitou and Yoshida (1994)
	soil organic carbon	Luo et al. (2015); Schonbeck and Evanylo (1998)
	soil texture	Arora et al. (2011)

2.4.2 Soil temperature

Soil temperature is an important environmental parameter for plant growth. Obviously, soil temperature is more crucial than air temperature for agricultural operations. It influences aeration, soil moisture content, and the availability of plant nutrients. Different types of mulching materials can modify soil thermal regimes which lead to better crop production (Pramanik et al., 2015). Mulching materials control soil temperature, which can augment or reduce crop yield. Modification of crop microclimate by mulching the soil alters soil temperature and affects plant growth and yield (Lamont, 2005). In general, the effect of mulches on the temperature regime of soil varies depending on capacity of the mulching materials to reflect and transmit solar energy (Lamont, 2005). Mulches reduce soil temperature in summer and raise it in winter. Mulches alter soil temperature, which affects the thermal regime of a soil (Arora et al., 2011; Pramanik et al., 2015). Olasantan (1999) obtained higher soil temperature during colder weather and lower soil temperature during warmer weather under mulching compared to non-mulched soil. Although, biodegradable film mulching provides lower temperature compared to polyethylene film mulching (Moreno and Moreno, 2008), the former could be disadvantageous, especially, in hot climates due to early decomposition and advantageous in cool conditions to maintain warm temperature at night that enables faster seed germination. Various mulching materials also cause fluctuation of daily soil temperature in the upper (5 cm) soil layer; the soil temperature however remains almost invariable in the deeper layers (Herbert, 1964).

Paper mulching lowers soil temperature as compared to black plastic mulching or bare soil and provides the lowest soil temperature (Haapala et al., 2014; Runham et al., 1998). Organic mulches reduce heat conduction into the surface soil by retaining incoming solar radiation (Komariah et al., 2008). These mulches reduce the maximum soil temperature but raise the minimum soil temperature (Begum et al., 2001), while they significantly reduce soil temperature (Sinkevičienė et al., 2009). Zhang et al. (2009) recorded a 4°C decrease in soil temperature in the warmer period and a 2°C increase in soil temperature in the colder period at 10 cm soil depth. The timing of soil temperature measurements and mulching thickness also cause variation in soil temperature (Zhang et al., 2009). Tillage operation influences soil temperature since it loosens soil and enhances air exchange between the atmosphere and soil pores with a consequent increase in soil heat storage (Bandyopadhyay et al., 2009; Zhang et al., 2009). The plastic film mulching absorbs solar radiation and reduces soil heat loss with a consequent increase in soil moisture and temperature, both of which augment plant growth and improve crop production (Zhou et al., 2009; Xiukang et al., 2015). The effects of soil temperature on crop growth are, however, related to the climatic locations where the crop plants are grown. For example, Chakraborty et al. (2008) found that increased soil temperature under mulch did not increase the yield of wheat in India. In some regions, farmers need to lower soil temperature for higher yield, while in other regions, they need to increase soil temperature for higher yield (Haapala et al., 2014).

2.4.3 Effects of mulch color on soil temperature

Soil thermal regime, a crucial factor for plant growth and development, is influenced by the color of plastic film mulch. Color of the mulching materials determines the energy radiating factors (Lamont, 1993); it influences surface temperature of the mulch and the underlying soil temperature. However, the effect of mulching materials on soil temperature is highly variable; it depends on the type of mulch and color of the plastic film. Black plastic mulch increases soil temperature (Ibarra et al., 2012), but silver color plastic mulch reduces it compared to the bare soil (Lamont, 1993). The silver color plastic having high reflectivity, and low absorptivity and transmissivity may be a good selection for tropical regions (Angima, 2009; Sanders, 2001). Transparent plastic film is preferred for soil solarization since it increases soil temperature considerably (Komariah et al., 2011). Black, silver and transparent are the common colors of plastic film mulches that have been in practice commercially in vegetable production. The other colors of plastic film can be red, blue, gray, orange, green and yellow (Ngouajio and Ernest, 2004). The colors of the film influence crop yield by providing different soil temperature regimes. For example, black, transparent and red plastic film mulches can raise soil temperature more than that by silver and green mulches (Lamont, 1993). Transparent plastic mulch is favorable for solarization, which increases soil surface temperature (Komariah et al., 2011); this mulch, however, enhances weed growth. On the other hand, black plastic mulch is opaque and therefore can control weeds in addition to preventing evaporation (Zheng et al., 2017), while silver colored plastic mulch is especially suited for repelling insects (Balathandayutham et al., 2017). The short-wave reflection, long-wave radiation, total radiant energy and latent heat flux that significantly control soil hydrothermal characteristics are influenced by color of the plastic film (Filipović et al., 2016). The film color of the mulch also controls aeration around the plant and soil salinity (Balathandayutham et al., 2017).

2.4.4 Soil microbiology

Both soil moisture and temperature being substantially influenced by mulching affect soil microbiology. The type and color of the mulching materials also control soil microbiological properties (Moreno and Moreno, 2008). Organic mulches add nutrients to the soil when decomposed by microbes, help in carbon sequestration (Ning and Hu, 1990) and work as fertilizers after use. These mulches increase soil nutrients after decomposition under appropriate water and temperature levels (Chalker-Scott, 2007). Generally, green crops and animal manures, used as mulch, supply nutrients at higher rates than the other mulches like straw, wood chips and bark. The plastic film residue reduces soil porosity and hence air circulation, changes microbial communities and leads to low soil fertility (Yan et al., 2010). The higher soil temperature under plastic film mulch promotes soil microbial activity and speeds up decomposition of organic matter in the soil (Wang et al., 2016). Furthermore, soil moisture plays an important role in the level of soil microbial biomass carbon, as Smith et al. (1993) reported a strong correlation between the soil moisture and soil microbial biomass carbon. Plastic mulch accelerates C/N metabolism, eventually depleting soil organic matter stocks, increasing soil water repellency and favoring the release of greenhouse gases (Steinmetz et al., 2016). In addition, the functional diversity of both microbial biomass and microbial community plays a role in plant litter decomposition and carbon cycling in forest ecosystems (Carney and Matson, 2005). The biological and chemical properties of soils play an essential role for the regulation of organic matter decomposition, carbon sequestration and nutrient mineralization that are crucial for soil health.

Mulching stimulates soil micro-organisms such as algae, mosses, fungi, bacteria and other organisms like earthworms. Under plastic mulching with ridge-furrow system in India, Subrahmaniyan et al. (2006) reported 2, 12 and 12% increased population of soil bacteria, fungi and actinomycetes, respectively compared to the non-mulched treatment. In the study of Komariah et al. (2011), the combination of rice bran and transparent plastic mulching raised the earthworm populations at 5 cm depth. Soil microbial biomass carbon is a sensitive indicator of microbial activity that reflects soil quality (Benintende et al., 2008). Bacterial populations increase under organic mulches due to different chemical compositions and decomposition rates of organic materials (Mukherjee et al., 1991). Mulching treatments augment the total soil nitrogen compared to the bare soil (Ren et al., 2007); the increased nitrogen is, probably, attributable to an increased nitrogen metabolism by nitrogen-fixing of the organic mulching that stimulates protein production of the bacterial community in nitrogen cycles. Improper application/incorrect installation of mulches, on the other hand, creates an anaerobic environment under heavy rainfall situation, causing loss of nitrogen by denitrification (Acharya et al., 2005). To sum up, mulching materials alter the structure of soil microbiology and diversity due to changes in soil moisture and soil temperature. Addition of organic matter to the soil from organic mulches is, therefore, very important.

2.4.5 Soil physico-chemical properties

The interactions between soil and crop are influenced by clay content, temperature and moisture content of the soil, and oxygen availability in the soil (Powlson et al., 2011). In the study of Smets et al. (2008), mulching materials at the soil surface improved soil hydrologic characteristics by affecting the soil physical and chemical properties. Soil water environments are directly related to soil moisture and temperature that have significant impacts on soil physics and soil microbiology. Various research activities done on the effects of mulching on specific factors of soil environment are enumerated in **Table 2.3**. The mulches reduce deterioration of soil quality by preventing runoff and reducing soil loss that improves soil aeration, soil structure, organic matter content and physical properties of the soil (Jordán et al., 2010). Also, the increased rate of mulch application increases soil porosity, improves aggregate stability and organic matter content, and reduces soil bulk density. Organic mulches are very effective to improve soil quality and increase crop yield (Sinkevičienė et al., 2009). These mulches incorporate organic matter into soil that increases Cation Exchange Capacity (CEC) of the soil with a resulting increase in soil electrical conductivity (Chen and Weil, 2010). Plastic mulch, on the other hand, under ridge-furrow systems, improves soil fertility by reducing exhaustion risk of organic carbon and nitrogen of the soil (Liu et al., 2015). The straw mulch affects hydrothermal regime of soils by increasing soil temperature and reducing soil water evaporation (Arora et al., 2011). This mulch dampens the influence of environmental factors on soil by increasing soil temperature and controlling seasonal fluctuations of soil temperature (Li et al., 2013). It also enhances the soil biotic activities of earthworms (Lal, 1998) and other soil fauna that improve the soil structure and quality (Döring et al., 2005). The effect of mulching on soil bulk density varies depending on type and properties of the soil, type of mulch, climate and land use (Mulumba and Lal, 2008). Mulching increases soil bulk density in case of conventional tillage (Bottenberg et al., 1999) but reduces it by adding organic matter to the soil (Unger and Jones, 1998); such increase or decrease in soil bulk density depends on specific situations. The application of mulch also augments total porosity, aggregation and moisture content of the soil (Mulumba and Lal, 2008). Lumbanraja et al. (2004) found weed as a cover plant in coffee fields to be effective to improve soil chemical properties and maintain soil fertility. For the hilly humid area of Indonesia, Afandi et al. (2003) reported that paspalum conjugatum (buffalo grass), covering the soil surface in coffee fields, improved soil physical conditions with the consequent increase in organic carbon, aggregates stability, porosity and available moisture content of the soil. Mulches protect the soils from wind and water erosions, which contribute directly to root stress and plant health (Chalker-Scott, 2007). Soil physical properties are influenced by soil environment that is greatly related to soil moisture and soil temperature. Several studies (e.g., Ren et al., 2007; Zhao et al., 2009) showed that the ridge-furrow planting under straw or plastic mulching increased soil water infiltration, and prevented surface runoff and loss of top soil from farmland.

2.4.6 Carbon budget of mulching methods

The chemical and biological quality and functioning of the soil play an essential role for the regulation of organic matter decomposition, carbon sequestration and nutrient mineralization. Significant quantity of soil organic matter loss occurs within one to three years of mulching due to temperature-induced accelerated biodegradation (Moreno and Moreno, 2008; Li et al., 2004; Li et al., 2007; Zhang et al., 2015) that are closely linked and entangled with decreasing C/N ratios (Jia et al., 2006; Zhou et al., 2012). Higher temperatures for soil solarization may even deplete up to 85% of soil carbon in less than one month (Simmons et al., 2013). But, soil organic matter contents remain stable during one to two years of plastic mulching when the soil carbon pool is maintained by organic matter input from crop residues or additional vegetative mulching (Schonbeck and Evanylo, 1998; Tindall et al., 1991). However, it is still unknown under which conditions and to what extent changes in soil organic matter contents are governed (Steinmetz et al., 2016). This knowledge is particularly relevant for estimating carbon storage in intensive land use scenarios and agricultural practices in which the majority of plant materials is removed at harvest (Chapman et al., 2012; Pardo et al., 2012; Tian et al., 2012). So, for soils with limited natural carbon input, a strict soil organic matter budgeting is required to avoid soil degradation (Zhang et al., 2015) and preserve soil health (Stork and Eggleton, 1992).

2.5 Impacts of mulching

2.5.1 Positive impacts

Both organic and inorganic mulches exert profound effects on microclimates, agronomic productivity and yield of crops (Atreya et al., 2008). Several research works describing the impacts of mulching materials on agricultural environment are listed in **Table 2.4**.

Table 2.4 Impacts of mulching on agro-environment.

Parameter	Indicator	References
crop yield	maize	El-Wahed and Ali (2012); Xu et al. (2015a); Mbah et al. (2010)
	wheat	Cai et al. (2015); Yang et al. (2006); Chakraborty et al. (2008)
	soybean	Arora et al. (2011); Siczek et al. (2015); Siczek and Lipiec (2011)
	potato	Dixit and Majumdar (1995); Xu et al. (2015b); Zhao et al. (2014)
	tomato	Moreno and Moreno (2008); Ogundare et al. (2015); Chakraborty and Sadhu (1994); Schonbeck and Evanylo (1998)
	groundnut	Subrahmaniyan et al. (2006)
	cabbage	Tiwari et al. (2003)
	watermelon	Ghawi and Battikhi (1986)
	pineapple	Komariah et al. (2008)
agronomic	weed control	Jeon et al. (2011); Abouziena and Radwan (2015); Boyhan et al. (2006); Jenni et al. (2004)
	insect populations	Andow et al. (1986); Kring and Schuster (1992)
	pest management	Brown et al. (1993)
	diseases control	Lamondia et al. (1999)
	root characteristics	Rahman et al. (2005); Wein et al. (1993); Rathore et al. (1998)
crop climate	evaporation	Zribi et al. (2015); Ji and Unger (2001); Begum et al. (2001)
	microclimates	Waggoner et al. (1960)
	radiation balance	Liakatas et al. (1986); Bittelli et al. (2008)
	GHG emission	Cuello et al. (2015)

GHG: Greenhouse gas

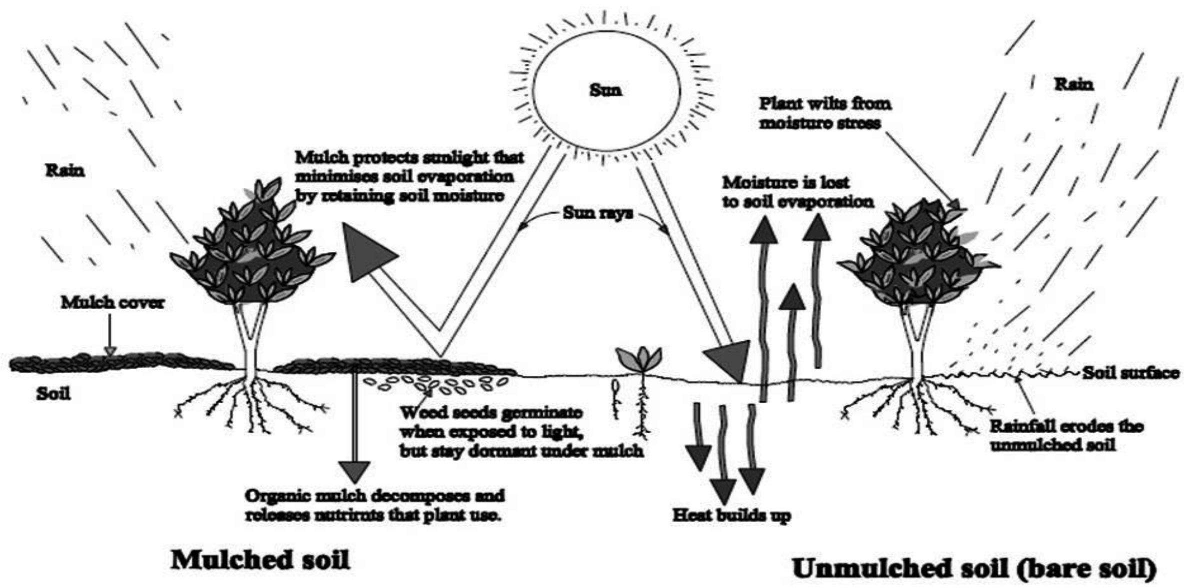

Figure 2.2 A conceptual framework of working principles and benefits of mulching.

In agricultural science, plant agronomy is considerably influenced by microclimates; it is an important indicator for improved production. Mulching materials greatly influence the microclimates that have positive or negative impacts on plant physiology and crop yield. Straw and plastic mulching was found to increase chlorophyll content of crops (Yang et al., 2006). Sekhon et al. (2005) found increased chlorophyll content of soybean leaf under straw mulching. Mulch layer can inhibit certain plant diseases as well. For instance, mulching with sawdust relieved shoestring root rot (Armillaria mellea) and the use of glossy-leafed Brassica plants has shown promise in reducing various lepidopteran and aphids inhabiting crucifer crops (Stoner, 1990). The reduction in diseases was significantly correlated with increased soil biological activity (McMillen, 2013). The physical barrier of mulch cover reduces the germination and nourishment of many weed species. For example, weed growth is more likely in organic mulches than in inorganic mulches (Relf and Appleton, 2009). Thus, the mulching materials, depending on their characteristics, can suppress the weeds, diseases, insects and pests. In the experiment of Moore et al. (1994), triticale cover crop mulches reduced the weed compared to the bare soil; the reduced weed put considerable positive impact on soybean yield. The working principles and the resulting benefits of mulching are conceptualized schematically in **Fig. 2.2**. Comparing the effectiveness of inorganic (e.g., plastic) and organic mulching materials to control soil evaporation, Zribi et al. (2015) reported that the plastic mulching increased water use efficiency by 20–60% due to reduced evaporation. Various mulching materials greatly influenced plant height and bulb diameter of garlic (Iroc et al., 1991). The transparent plastic mulch reduced whitefly and aphid populations, and virus diseases (Brown et al., 1993). The mode of action of the transparent plastic mulch is thought to be the result of high reflectance of UV light (Kring and Schuster, 1992). Thus, mulches, when applied to the agricultural fields, have a lot of benefits, including: (i) reduction of: soil moisture loss, soil compaction, soil erosion, impact of water droplets hitting the soil surface, weed growth and competition for water and nutrients from the surrounding fields, (ii) encouragement of earthworm movement into the soil that helps to improve soil structure and nutrient cycling, (iii) keeping the underlying root zone warmer in winter and cooler in summer in order to reduce root damage, (iv) providing a barrier for trees against lawn mowers and weed whips, (v) helping top growth and root development of plants, (vi) improving appearance of newly planted trees, (vii) lowering soil pH to enhance crop root's ability to take up nutrients, and (viii) increasing long-term nutrient availability in the soil.

2.5.2 Negative impacts

Although, mulching has many advantages, it has some negative effects. The major negative consequence of the use of plastic mulch in agriculture is related to handling the plastic wastes and the associated environmental impacts. The plastic film mulching significantly reduces soil organic matter and greatly increases greenhouse gas emissions (Cuello et al., 2015). Plastic waste management is a major problem of plastic film mulching (Kyrikou and Briassoulis, 2007). Plastic mulches create difficulties in dumping and emit harmful substances during burning (Lamont, 1993). They promote soil degradation, cause soil water repellency and occur as potential pollutants in the soil (Steinmetz et al., 2016). It becomes problematic in top dressing of fertilizer when plastic mulches are used. Costly and specialized equipment, such as bed presses and drip tape layer, are required to install plastic mulches. Manual installation of plastic mulch is also time consuming and labor intensive, and hence costly. Removal of the mulching films from the field is also associated with considerable labor cost (Malinconico et al., 2008).

Sometimes, the natural mulches are not good for weed control (Boyhan et al., 2006). For example, certain types of mulches such as straw, hay and grass contain seeds, which may become weeds. Organic mulching materials such as wood chips and bark may occur as soil acidifiers (Chalker-Scott, 2007). Too much organic mulch can lead to excess moisture, creating new problems such as pests, anaerobic conditions and rotting of the roots that can damage the plants. Straw mulches often contaminate the soil and deplete the seedbed nitrogen due to their high carbon-to-nitrogen (C/N) ratio (Kasirajan and Ngouajio, 2012). Moreover, when carbon rich materials such as straw or stalks are used for mulching, nitrogen from the soil may be used by microorganisms for decomposing those materials. Thus, nitrogen may be temporarily not available for plant growth (risk of N-immobilization) (INFONET-BIOVISION, 2010). Paper mulch, especially newspaper, degrades most rapidly, and it becomes difficult to cover a large area by newspaper (Sanchez et al., 2008).

2.5.3 Impacts on ecosystem services

Impacts of plastic mulching on ecosystem services are an important and critical issue. Ecosystem services are the benefits that a society attains from ecosystems (Millennium Ecosystem Assessment, 2005). One key aspect of all ecosystem services is biodiversity since the stability of an ecosystem depends on the interaction between its non-living components and living organisms (Haines-Young and Potschin, 2010). Plastic mulching can potentially modify soil conditions in several ways. The surface of the mulched ridges enhances water runoff into furrows, which become particularly susceptible to soil erosion and loss of soil structural stability (Rice et al., 2001; Wan and El-Swaify, 1999; Zhang et al., 2013). Soil solarization method, applied before planting to eradicate soil borne pathogens and devitalize weed growth (Horowitz et al., 1983; Tamietti and Valentino, 2006), promotes fungicide dissipation from the soil (Fenoll et al., 2010). Plastic mulch may also cause soil water repellency (Ahmed et al., 2015; Carminati, 2013) and an increased uptake of heavy metals by plants (Moreno et al., 2002). The modified soil conditions are thought to accelerate soil degradation and may lead to undesirable shifts in soil organism communities and affect ecosystem engineers such as earthworms or nematodes (Steinmetz et al., 2016). Plastic mulches further generate significant amounts of non-degradable and hardly recyclable waste (Delgado and Stenmark, 2006), which is likely to pollute the environment either through incineration emissions, landfill leaching or micro plastic residues. Thus, plastic mulching may pose a significant risk to sustaining the essential ecosystem services in agricultural landscapes. Hence, the impacts of plastic mulching on ecosystem services need due attention.

2.6 Suitability of mulching

Mulch can be used in fields before and after crop planting, as well as around young plants. It is especially useful for high-value vegetable crops and for growing crops in dry areas during dry season cropping and in places where the soil is easily eroded by heavy rains (Li et al., 2013). The use of plastic film mulch in agriculture is generally recommended for profitable row crops. Use of plastic mulch has the advantages of being light weight, easy handling and better coverage compared to organic mulch (Haapala et al., 2014). Excessive application of mulch to the field may adversely effects on pathogen and contaminates the soil. But, most of biodegradable mulches do not have any additional advantages in terms of crop production over plastic mulch (Adhikari et al., 2016; Moreno et al., 2017). With these limitations, biodegradable mulch is still far from wide adaptation for crop production. In broad, the choice of selection of an appropriate mulching material depends on types of materials, ecological locations, colors, thickness, perforations and availability of materials, cost-effectiveness and feasibility of the crop (Wang et al., 2015). The comparative attributes of selection of organic and plastic mulching are discussed in **Table 2.5**.

Table 2.5 Comparison of various characteristics between organic and plastic mulching.

Subject	Organic mulching	Plastic mulching
Materials type	bio-based cellulose, chips, leaf	acetate, polyethylene, polymeric material
Durability	temporary and decay over time	long-lasting, 2–3 crop seasons
Thickness	3–5 cm, varies with application rate	15–20 µm; 15 µm is most effective
Colors	natural	black, silver, white, red, blue, yellow etc.
Weed control	effective but grass grows weed	highly weed competition except white color
Solarization	not effective in most of the cases	most effective by boosting soil temperature
Pest management	reduces thrips, and fungal disease	reduces spider mites, and whiteflies.
Fragments	degradable to soil	problematic and contaminated after 1–2 seasons
Availability	locally available	not locally available
Priority mulch	straw (rice and wheat)	black plastic
Costing	cheap	expensive
Labor	less laborious	laborious during setting and removing
Degradability	naturally decompose	discarded and buried that polluted soil
Plant growth	moderate growth	fast growth and earlier harvesting
Water infiltration	increases	restricts water flow

2.7 Economic aspects of mulching

So far, the main interests and criteria of an agronomic evaluation of plastic mulching have largely been determined by measuring short-term benefits, first of all the higher annual marketable yields. Although many studies have demonstrated that the use of plastic mulch increases product quantity and quality (Laugale et al., 2015; Overbeck et al., 2013; Ruíz-Machuca et al., 2015), it remains unresolved under which specific conditions the revenues offset the costs of plastic mulch purchase, management and disposal (Fisher, 1995; Mugalla et al., 1996). In this regard, scientific literature is still scanty and contradictory as well. Generally, the most pronounced economic effects reported in the literature have been achieved by water savings (up to 25%) and reduced labor costs for weed and pest control (Ingman et al., 2015; Jabran et al., 2015). These economic effects have taken into account only the basic assets, such as material acquisition and marketable resource consumption, without calculating the effort to apply and remove the plastic covers (Steinmetz et al., 2016). Although, plastic mulch provided better yield (Mehan and Singh, 2015), but in many cases, straw mulch has been recommended for its convenience because of locally available mulch materials (Yin et al., 2016). Plastic and geotextile mulches may not be available in some countries and, also, they are more expensive than organic mulching. The organic materials (e.g. straw, leaves, cut grass), on the other hand, are almost available everywhere that can be easily collected by farmers. However, comprehensive knowledge of the overall costs and benefits of plastic mulches in the scientific literature is still scarce and incomplete. More detailed and comparative analyses on the life cycle of plastic mulches are needed under particular consideration of their long-term agronomic viability and environmental impact over long period of application (Ayala and Rao, 2002).

2.8 Importance of numerical simulations on various mulching

Numerical modelling is an effective way to explore water and heat flow distributions in soil ecosystems (Qi et al., 2018). Numerical simulations approaches are varied from analytical and semi analytical solutions to more composite numerical codes that account huge number of concurrent nonlinear processes. Numerical models are extensively used because of their availability in public and commercial domains, and also sophisticated graphics-based interfaces are available (Chen et al., 2018; Li et al., 2015). Recently numerical modeling studies are increasingly applying to simulates soil, water and plant growth data. Various numerical models are available in the literatures for simulating soil water, heat and nutrient transport and their distribution in soil profile along with prediction of important crop growth parameters. Understanding of water and heat transfer mechanism through mulching soil is crucial to increase the availability of mulching use in agricultural farmland (Liu et al., 2018). Moreover, root water and nutrient uptake is one of the most important processes in the irrigation management which can be considered into numerical simulation approach. It is still unknown in what amounts of water saved by mulching which is critical due to influences the mulch materials by microclimate, soil environment and plant growths (Steinmetz et al., 2016). Therefore, water and heat transport through the soil profile under different mulching types are greatly controlled by the characteristics of surface covers, soil properties and climatic environment. Therefore, numerical modeling approach of various mulching materials may need to concern for efficient water use. Organic mulching protects direct rainfall infiltration and plastic mulching restricts water flow to soil profile. For example, the modeling effects of water vapor flow and heat transfer process through various thickness organic mulched soil in response to crop growth in different climatic regions may have an attention in future research (Kader et al., 2019). The mechanism of coupled transport of water, heat and vapor through organic mulching is entirely different from plastic mulch due to different characteristics of materials. Moreover, plastic mulch protects download water flow but enhances lateral water flow on the surface. In contrast, organic mulch materials having higher porosity work like coarse soil and modify water and heat flow rates. Rainwater flows through the fabric of straw mulch to soil profile, but plastic mulch restricts water infiltration. Consequently, proper selections of boundary condition and soil hydraulic parameters are crucial for simulations under mulching surface which may be needed to investigate in depth.

HYDRUS-1D (Šimůnek et al., 2013) is a popular Windows-based modeling software for simulating water, heat and multiple solute transport in one dimensional variably saturated porous media. It provides quick and accurate solutions due to the flexibility of selecting boundary conditions (Zhao et al., 2010) and soil hydraulic functions (Saito et al., 2006). Numerical simulations of mulched soils using HYDRUS-1D are, however, complicated due to interactions of the mulch and soil surface, and difficulty in correct consideration of boundary layers and accurate estimations of soil evaporation (Li et al., 2015; Šimůnek et al., 2016). Vapor transport is an important part of total water flux in dry soil (Scanlon et al., 2003; Saito et al., 2006), and organic mulching may have a significant role to control vapor flow under the covered soil. Vapor transport occurs from the permeable surface of the organic materials, while the impervious plastic film covers restrict the vapor flows. So, a numerical model may help to effective soil water and thermal management of various mulching practices.

2.9 Future research

A comprehensive study is required to investigate soil biodiversity and climatic interaction with soil under different mulching materials. Until now, only a few researches have been done to determine the amount of greenhouse gas emission under mulching (Nawaz et al., 2016; Petitjean et al., 2015) and the influence of soil temperature on the movement of nitrogen and other nutrients through mulching materials under various rainfall conditions (Gan et al., 2012). Impacts on ecosystem services of plastic mulching and its long-term agronomic assessments need further investigation (Steinmetz et al., 2016). Plastic mulches have well-known negative impacts on the environment, but the risk of pollution needs to be comprehensively analyzed. Many researchers have been developing new type of mulching materials like paper-based materials, spray-able polymer film, geo-textile, and bio-based and compostable plastics that might be important in future research for long-term interaction between soil and water environment. The future research is therefore needed to investigate the effects of biodegradable mulching materials on crop growth, microclimate modifications, soil biota, soil fertility and crop yields (Kasirajan and Ngouajio, 2012). Moreover, research will also be necessary for cost minimization of these materials so as to make them convenient for farmers, since the biopolymer-based mulching materials are still expensive. Moreover, the brief comparison is necessary to select suitable types of mulch materials depending on crop variety and climatic regions. Further studies including suitable mulching application rates and plant response are required. Moreover, the recycle paper-based mulch such as newspaper releases ink to soil surface (Haapala et al., 2014) which causes physicochemical interactions with soils required deep investigation in future. Several investigators (e.g., Ibarra-Jiménez et al., 2011; Xue et al., 2017) studied the effects of color of plastic mulch on crop growth and yield in different microclimates, but the influences of film colors on soil water and heat regulation under soybean growth have been little examined yet. Moreover, the further research is needed on soil surface energy balance of different color of plastic mulching to understand how extend of microclimate modifies by film mulch. The interactive effects of soil water in terms of soil heat capacity and thermal conductivity under mulching soil need to be modeled in future. Therefore, the numerical model is required to focus the interactions among soil, mulch and plant canopy interface. It may create new window to future opportunity for efficient use of mulching system in the agricultural soil.

2.10 Conclusions

The various mulching materials affect soil hydrothermal regime, which alters moisture and temperature environment of the soil. These alterations in soil environment influence soil microbiology, which is essential to create favorable soil environment for plant growth. The mulching materials, by modifying the microclimate and reducing soil evaporation, exert significant impact on the water-saving in agriculture. However, every type of mulch has some strengths and weaknesses, making it suitable for some situations and not for others. Availability, durability and cost of the materials are the important issues to be taken into considerations for the selection of mulching materials. The main focus should however attribute to reduce the negative impacts of mulching. The organic mulching saves the labor cost and, after decomposition, adds plant nutrients to soils; this is an extra advantage of the organic mulches over the plastic mulches. In order to get maximum benefit from mulching, it is imperative to investigate the effects of different mulching materials under various field conditions for the best fit of the materials to the crop and climate. The color and application rate of the mulch are highly influenced by the selection of mulching material that absolutely depends on farmers' choice. It is emphasized that integration of different mulching approaches can save and conserve the water resources substantially and lead to satisfactory crop yields.

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CHAPTER 3

General methodology

3.1 Study site and land preparation

Field experiments were done in two consecutive years (May–August of 2015 and 2016) at Gifu University farm in central Japan (35° 27' N and 136° 44' E, 12 m above sea level) for cultivating of rain-fed soybean crops. The experimental field was in upland area of the farm where tomato crop was cultivated in the previous year. The Japanese soybean cultivar Meguro (*Glycine max cv. Meguro*) was used in the experiments. A 120 m^2 area was selected for experiment. The field was ploughed thoroughly with a tractor up to 15 cm depth in each year. The applied fertilizer doses were organic manure (25 t ha^{-1}), chemical fertilizer (4 t ha^{-1}) and Magnesia Lime Carbonate (1 t ha^{-1}), which were recommended by fertilizer manufacturer (Nakanihon Nousan Co. Ltd., Japan). Raised bed of 5 cm height was prepared for each treatment plot. The size of each plot was 12.5 m^2 (5 m × 2.5 m) and there was a buffer zone of 0.5 m surrounding the treatments. The entire raised bed of each treatment was covered by spreading mulch manually.

3.2 Treatment descriptions

The experiment was carried out by four different mulching treatments in 2015 and five mulching treatment in 2016 with a control (bare soil). Bare soil (no-mulch) was common treatment in both years and was compared with various mulching treatment (**Fig. 3.1**). The detail specifications and conditions of treatments were listed in **Table 3.1**.

Table 3.1 The treatment descriptions and mulching application rates.

Year	Mulch treatment	Mulching materials	Remarks
2015	Straw	Rice straw	0.50 kg m^{-2} (dry weight)
	Paper	Shredded newspaper	0.30 kg m^{-2} (two layers)
	Plastic mulch	Silver color plastic film	20 µm thickness
	Plastic-hole	Silver plastic with uniform 4.5 cm holes	(single layer film)
	Bare soil	No-mulching (control)	-
2016	Straw	Rice straw	0.50 kg m^{-2} (dry weight)
	Paper	Shredded newspaper	0.30 kg m^{-2} (two layers)
	Silver plastic mulch	Silver color plastic film	20 µm thickness
	Black plastic mulch	Black color plastic film	(single layer film)
	Clear plastic mulch	Transparent color plastic film	
	Bare soil	No-mulching (control)	-

Figure 3.1 A field layout with various mulching treatments used in the experiments.

Dry rice straw mulch was spread manually on soil surface over the entire raised bed in the mulching plot at 0.5 kg dry straw per square meter and no-mulch material was applied in the bare soil treatment. The strip length for rice straw was 50–60 cm. The thickness of straw on soil surface was approximately 3 cm. The colored plastic mulches were black plastic mulching (BPM), silver plastic mulching (SPM) and transparent plastic mulching (TPM) used in the year of 2016. The thickness of the plastic film of each color was 20 µm, and only one layer plastic film was used for each mulch plot. We designed a new application method for film mulch that provided a perforated plastic mulching with open holes in the film. The diameter of planting hole for each soybean plant was 3 cm and that of additional plastic hole was 4.5 cm. The additional holes were located between two adjacent rows and between two adjacent columns of soybean plants. Thirty five (35) uniform circular holes were made between the rows and between the columns of the crop at 40 cm interval on the plastic film for the plastic-hole mulching treatment; total area of the perforated extra holes (excluding the planting holes) was 556.5 cm^2 (0.45%).

3.3 Data measurements

Climatic data pertinent to soybean cultivation such as rainfall, air temperature, relative humidity and solar radiation were measured by installing a weather station at the experimental site. The average monthly climatic data are presented in **Table 3.2**. Reference evapotranspiration (ET_o) was calculated from the climate data by using Penman-Monteith method (Allen et al., 1998). Moreover, the US Class A pan was set up in the field to measure daily evaporation at the experimental field. Daily pan evaporation data was recorded in everyday morning at 8:00 AM. The average pan evaporation was 3.9 mm d^{-1} (except the rainy days) during the study period. The soil moisture and temperature were measured for each treatment throughout the experimental periods. Necessary sensors were installed horizontally at the center, between the rows and between the columns of each treatment, and the entire raised bed of each plot was covered with a mulch material by ensuring maximum contact of the mulch with soil surface. Each depth had one sensor and the sensors were connected to data loggers. The hourly volumetric soil moisture content was monitored at three different depths (5, 15 and 25 cm) in each treatment using two different types of sensor. Frist one is, 2 rod TDR (CS615) connected to data logger (CR10X) (Campbell Scientific Inc., USA). Second one is, 5 TM (Temperature Integrated with Soil Moisture sensor, Decagon Devices, Int., USA) was connected with Em50 data logger to record hourly soil moisture and temperature. Also, the total 9 numbers of TMC20-HD temperature sensor (Onset Computer Corporation, USA) connected with 3 temperature data logger U12-008 (Onset Computer Corporation, USA) that covered on the three treatments in three depths (5, 15 and 25 cm). Furthermore, soil temperatures of another three treatments were measured by setting Decagon 5TM sensors. The position of sensors and logger's in the fields are given in **Appendixes 1** and **2**.

3.4 Weather conditions

The microclimate for soybean growth was different in 2015 from 2016 due to yearly variation of air temperature and rainfall (**Fig. 3.2**). Daily mean air temperature during the periods of experiments (18 May – 27 August 2015 and 26 April – 14 August 2016) varied from 22.0 to 28.4°C in 2015 and 20.6 to 30.0°C in 2016 (**Table 3.2**). Mean air temperature during the soybean cultivation period was 24.8°C in 2015 and 25.4°C in 2016. Air temperature increased with the progress of soybean growth from June to August (**Fig. 3.2**). Monthly maximum air temperature was 37.4°C in 2015 and 41.5°C in 2016, both temperatures occurred in the month of August (**Table 3.2**). The crop received 874 mm and 705 mm rainfall during its growing period in 2015 and 2016, respectively. The soybean was cultivated under

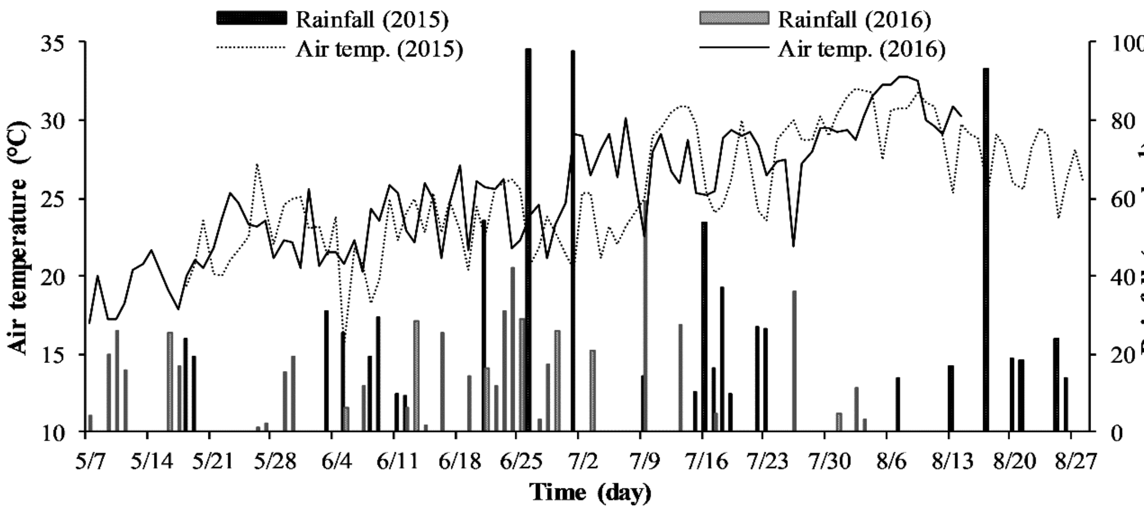

Figure 3.2 Daily mean air temperature and rainfall in the study area during the soybean growing seasons of 2015 and 2016.

Table 3.2 Average monthly climatic data of the experimental site for soybean growing period (May–August) of 2015 and 2016.

Year	Period	ET_o (mm d^{-1})	Solar radiation (MJ m^{-2} d^{-1})	Air temperature (°C)			Relative humidity (%)
				Max.	Min.	Mean	
2015	19 May~	4.9	12.7	34.6	14.0	22.0	67.3
	June	3.7	11.1	32.0	16.8	22.8	82.2
	July	3.6	12.5	36.1	21.4	26.8	86.4
	~ 27 August	5.7	17.0	37.4	22.6	28.4	82.1
2016	May	4.0	15.5	25.7	16.1	20.6	63.6
	June	4.5	16.8	32.5	17.6	23.6	80.1
	July	5.2	16.3	37.2	21.5	27.5	80.2
	August	6.1	17.1	41.5	22.9	30.0	73.9

rainfed conditions and no irrigation was applied. Mean daily ET_o was 4.5 and 5.0 mm day^{-1} in 2015 and 2016, respectively. ET_o was greater in 2016 than in 2015 due to higher solar radiation and air temperature in 2016 than in 2015 (**Table 3.2**).

3.5 Measurement of soil physical properties

After harvesting soybean in each year, undisturbed soil samples were collected from 0–10, 10–20 and 20–30 cm soil profiles with three replications by using core samplers of 100 cm^3. The soil samples were used to analysis soil physical properties (soil texture, water retention, hydraulic conductivity, soil particle density and soil bulk density) for each soil layers under various treatments. Soil texture was classified based on USDA classifications (**Table 3.3**). By plotting the values of the percentages of sand, silt and clay on the Marshall's Triangular coordinate, USDA soil textural classes of the soils was determined. The percentages of sand, silt and clay were determined for 0–10, 10–20 and 20–30 cm soil profiles by hydrometer method following Bouyoucos (1962). Soil organic matter was determined with the disturbed soil samples by ignition method following Storer (1984). Saturated hydraulic conductivities (K_s) of the field soil at 5, 15 and 25 cm depths were measured by falling head method (Klute and Dirksen, 1986). The average K_s of 0–30 cm soil profile was 2.6 cm h^{-1}.

Table 3.3 Particle size distribution and texture of the 0−10, 10−20 and 20−30 cm soil layers at the experimental field.

Soil layer (cm)	Particle size distribution (% weight)			Soil texture
	Sand	Silt	Clay	
0−10	52.8	31.2	16.0	Loam
10−20	55.8	30.5	13.7	Loam
20−30	74.0	18.9	7.1	Loamy sand

Table 3.4 Soil moisture contents at field capacity (θ_{FC}), permanent wilting point (θ_{PW}), available moisture (*AM*), total available water (*TAW*), bulk density (*BD*) and organic matter content (*OM*) of 0–10, 10–20 and 20–30 cm soil layers under three different mulching treatments during soybean growing seasons of 2015 and 2016.

Year	Treatment	Soil layer (cm)	θ_{FC} (cm^3 cm^{-3})	θ_{PW}	*AM* (mm)	*TAW* (mm)	*BD* (g cm^{-3})	*OM* (%)
	Straw	0–10	0.38	0.17	21		1.11	3.49
		10–20	0.35	0.14	21	61	1.19	2.82
		20–30	0.36	0.17	19		1.42	2.41
	Newspaper	0–10	0.38	0.18	20		1.21	4.33
2015		10–20	0.37	0.17	20	57	1.45	3.26
		20–30	0.32	0.15	17		1.20	2.79
	Plastic	0–10	0.40	0.17	23		1.16	3.48
		10–20	0.42	0.17	25	68	1.26	3.26
		20–30	0.36	0.16	20		1.48	2.3
	Plastic-hole	0–10	0.41	0.17	24		1.26	3.53
		10–20	0.36	0.18	18	64	1.42	2.98
		20–30	0.40	0.18	22		1.53	2.53
	Bare soil	0–10	0.37	0.14	23		1.13	3.66
		10–20	0.38	0.17	21	63	1.39	2.72
		20–30	0.34	0.15	19		1.43	2.00
	Straw	0–10	0.37	0.18	19		1.29	2.63
		10–20	0.34	0.15	19	58	1.39	1.88
		20–30	0.35	0.15	20		1.41	1.66
	Newspaper	0–10	0.34	0.15	19		1.18	3.09
2016		10–20	0.34	0.15	19	57	1.34	2.29
		20–30	0.33	0.14	19		1.30	2.17
	Black plastic	0–10	0.34	0.15	18		1.01	2.81
		10–20	0.31	0.14	16	50	1.37	1.64
		20–30	0.30	0.13	16		1.23	2.19
	Silver plastic	0–10	0.33	0.14	18		1.16	2.63
		10–20	0.36	0.17	18	53	1.26	2.31
		20–30	0.31	0.13	17		1.13	1.64
	Transparent plastic	0–10	0.32	0.15	16		1.12	2.70
		10–20	0.34	0.15	18	54	1.32	2.10
		20–30	0.36	0.15	20		1.44	2.13
	Bare soil	0–10	0.36	0.16	20		1.23	2.85
		10–20	0.32	0.14	18	54	1.35	2.46
		20–30	0.31	0.15	16		1.32	1.51

3.6 Determination of soil moisture retention

Soil moisture retention curve was derived from the collected soil samples by centrifugation method (Russel and Richards, 1938), using a Kokusan H-2000B centrifuge machine. In the centrifuge, each soil cylinder was inserted into a stainless sample holder provided by the centrifuge manufacturer. The Kokusan H-2000B centrifuge was equipped with a mechanism to maintain and control the inside temperature within the range of 16 to 21° C. For the centrifugation method, the soil samples were kept under constant rotation for 90 min to reach the soil water potential equilibrium corresponding to a given centrifugal force (Silva and Azevedo, 2002). After each centrifugation step, the samples were weighed and returned to the centrifuge to undergo a higher rotational speed. This procedure was done at –10 kPa,

–30 kPa, –100 kPa, –315 kPa and the last established water potential (–1500 kPa). The samples were then dried in oven at 105 °C for 24 h to determine their bulk densities. The measured soil hydraulic properties, bulk density and organic matter content under all treatments are listed in **Table 3.4**.

3.7 Agronomic practices

The growing period of soybean was from 10 May to 27 August (110 days) in 2015 and from 26 April to 15 August (111 days) in 2016. Soybean seeds were sown in the plots manually at 2–5 cm depth in four straight rows with spacing of 40 cm and seed-to-seed distance of 30 cm. The cultivation density was 10 plants per square meter and three seeds were sown in each hole. After few days of germination, only one healthy plant was kept; the other plants were carefully uprooted. The growth period of soybean, same under each treatment, was divided into vegetative stages (0–37 days after sowing, DAS), reproductive stages (38–80 DAS) and maturity stages (81–111 DAS). The crop was harvested at full maturity on 14 August 2016 (111 DAS). **Figure 3.3** shows the experimental photograph of soybean crop at different stages under various treatments. Weeding was done manually both inside and surrounding area (buffer zone) of the experimental plots as and when required. The weed biomass was recorded after drying the uprooted weeds at 60 °C for 72 h in oven. Plant height was measured with a linear scale and leaf chlorophyll content was recorded by a SPAD (Soil Plant Analytical Development) meter (SPAD-502; Konica Minolta, Japan) at 23, 47, 60 and 82 DAS. For each treatment, ten plants were selected from one square meter area for data measurements at harvest. The measured growth and yield attributes of soybean included nodulations, grains per plant, seeds per plant (each grain contains 2–3 seeds), root length, total seed weight per plant, grain and seed yields, and straw yield. For each treatment, the diameter of stem of ten plants was measured by a screw gauge. After drying the soybean seeds in oven at 58°C for 48 h, the weight of seeds was determined. Water use efficiency (*WUE*, g m^{-3}) of the crop was calculated by

$$WUE = \frac{Y}{10^{-3} \times SWC} \tag{3.1}$$

where Y is seed yield (g m^{-2}) and *SWC* is total seasonal soil water consumption (mm).

3.8 Statistical analysis

The growth and yield data of soybean were analyzed with R-package (foundation for statistical computing, http://www.R-project.org), and the means were compared based on Tukey's HSD (Honestly Significant Difference) test at 5% level of significance. Analysis of linear regression between the air temperature and soil surface temperature was done by using ggplot 2 package in R-software.

Figure 3.3 Soybean production stages under different mulching treatments.

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CHAPTER 4

Effects of organic mulches on soil hydrothermal regimes and rainfed soybean cultivation

4.1 Introduction

Mulching is one of the best soil and water management technologies that is crucial to restore soil moisture, reduce soil evaporation, alter soil temperature, maintain soil health and improve water use efficiency as well as crop yields (Chakraborty et al., 2008; Kader et al., 2017a). Although, plastic mulching is familiar in the contemporary agriculture to get temporary benefits on soil environment for increasing higher product yield (López-López et al., 2015), it brings adverse results of long-term effects on soil quality, farm profitability, environmental contamination and ecosystem services (Steinmetz et al., 2016). Organic mulch materials like straw, dry clips and shaded papers have several exceptional advantages over plastic mulch since they are cheap and environment friendly and add nutrients to soil after degradation (Kader et al., 2017a). Cereal straw is considered an ideal material for mulching because of its easy application in the field, and it works as an insulator of soil temperature during hot days and cold nights (Ghosh et al., 2006; Sarkar et al., 2007). However, straw being a thin material is difficult to spread uniformly on the field and, thus, exerts spatially non-uniform effects. On the other hand, shaded newspaper is non-toxic and biodegradable; it degrades naturally and incorporates into soil in relatively short period of time. One or two layers of newspaper, laid on the field, may modify water and heat environments in the root zone soil. Newspaper also controls weed seeds (Munn, 1992), and, sometimes, performs better than plastic mulch due to its eventual decomposition into soil (Ranjan et al., 2017). The cost of newspaper is also lower than straw and plastic (Haapala et al., 2014), and it is readily available and easy to use.

Soil moisture and temperature, greatly influenced by microclimates, are the vital factors to secure available water for plant growth, regulate optimum heat and maintain plant rooting patterns (Zhou et al., 2009; Ren et al., 2016). Organic mulching can suppress excess heat in soil and reduce fluctuation of daily soil temperature through latent heat of vaporization (Sarkar and Singh, 2007). These modifications of heat and soil moisture are important since rainfed soybean is very sensitive to water and heat stress, especially during its reproductive (flowering and fruiting) stage (Irmak et al., 2013). The temperature stress, appeared at high soil temperature in bare soil, can be minimized by using convenient organic mulches like straw and shaded newspaper. In addition, optimum soil temperature for soybean growth under mulching can be effective for safe water use and higher crop yield. Therefore, a clear knowledge is needed on soil environments, which influence water use efficiency and crop growth under different organic mulching, to obtain higher crop yields in sub-humid climates. Although, the effects of straw mulching have been well-studied (Kader et al., 2017a; Akhtar et al., 2019), no comprehensive research on the effects of shaded newspaper mulching on soil water consumption and extraction pattern under soybean cultivation was reported yet. Therefore, it is important to know the effects of organic mulching for altering soil hydrothermal regimes under rainfed conditions that may provide favorable environments for soybean cultivation. So, a two-year field experiment was done to investigate the effects of rice straw and shaded newspaper mulching materials on soil hydrothermal regimes (soil moisture and temperature, soil water consumption and its distribution in crop root zone), which affect growth, yield and water use efficiency of soybean under rainfed conditions in central Japan.

4.2 Materials and methods

4.2.1 Treatments

In this chapter, the effects of rice straw mulching (dry weight = 0.46 kg m^{-2}), recycling newspaper mulching (two layers, 0.30 kg m^{-2}) and no mulching/bare soil were evaluated under rainfed soybean.

4.2.2 Soil water consumption

Soybean is a shallow rooted crop with maximum rooting depth of 0–60 cm (Stone et al., 1976; Fan et al., 2016). Soybean root was concentrated in 0–30 cm soil depths from the observation. Moreover, the maximum rooting depth of soybean is 60 cm, of which 0–30 cm is considered as effective root zone (Fan et al., 2016). Therefore, 0–30 cm soil depth is considered as effective root zone in our study. Consequently, most of the water uptake by the crop occurs within the effective root zone depth. Soil water consumption (*SWC*) is the cumulative soil water reduction in the effective root zone between all consecutive rainfall events ($SWC_{i,j}$) throughout the soybean growing period. $SWC_{i,j}$ (mm) was estimated from the summation of moisture reductions in different soil layers (i =1～m) between two consecutive rainfall events (j =1～n) during the soybean growing season as

$$SWC = \sum_{j=1}^{n}\left(\sum_{i=1}^{m} SWC_{i,j}\right) = \sum_{j=1}^{n}\left(\sum_{i=1}^{m}\left(\theta_{RA,i,j} - \theta_{RB,i,j+1}\right) d_i\right), \quad \theta_{RA,i,j} \leq \theta_{FC,i} \tag{4.1}$$

where $\theta_{RA,i,j}$ (cm^3 cm^{-3}) is moisture content of ***i***-th soil layer just after ***j***-th rainfall event, $\theta_{RB,i,j+1}$ (cm^3 cm^{-3}) is moisture content of ***i***-th soil layer just before j+1-th rainfall event, $\theta_{FC,i}$ (cm^3 cm^{-3}) is moisture content of ***i***-th soil layer at field capacity (–33 kPa) (**Table 3.4**), d_i (mm) is thickness of ***i***-th soil layer, ***m*** is the number of soil layers and ***n*** is the number of major rainfall events. Three soil layers (0–10, 10–20 and 20–30 cm) and fourteen rainfall events were used to calculate *SWC* for the two years' experiments.

4.2.3 Total available moisture and soil moisture extraction

Theoretically, available moisture (*AM*) is the difference in soil moisture contents at field capacity and permanent wilting point that can be uptaken by plant roots. Total available soil water (*TAW*) is the total amount of available moisture in the effective root zone. *TAW* can be used to quantify the maximum amount of water that plants can extract from the effective root zone. The fraction of *TAW* that plant roots can easily extract from root zone is called the total readily available moisture (*TRAM*) (Allen et al., 1998). Both *TAW* and *TRAM* are useful indices to quantify the effects of mulching on soil moisture. *TAW* was calculated by

$$TAW = \sum_{i=1}^{m} AM_i = \sum_{i=1}^{m} (\theta_{FC,i} - \theta_{WP,i}) \cdot d_i \tag{4.2}$$

where $\theta_{FC,i}$ and $\theta_{PW,i}$ are the soil moisture contents ($cm^3\ cm^{-3}$) of ***i***-th soil layer at field capacity and permanent wilting point, respectively. Soil moisture extraction in the ***i***-th layer (SME_i) was calculated by

$$SME_i = \frac{\Delta\theta_i d_i}{\sum_{i=1}^{m} \Delta\theta_i d_i} \times 100 \tag{4.3}$$

where d_i is thickness of ***i***-th soil layer (cm) and $\Delta\theta_i$ is reduction of volumetric soil moisture content ($cm^3\ cm^{-3}$) of the ***i***-th soil layer between two consecutive rainfall events. In equation (**4.3**), SME_i, calculated for each soil layer, expresses the ratio of soil moisture reduction in the ***i***-th layer to the total soil moisture reduction within the effective root zone. By using soil moisture extraction ratio, SME_i, of each soil layer, $TRAM_i$ was estimated by

$$TRAM_i = \frac{AM_i}{SME_i} \tag{4.4}$$

Amongst the values of $TRAM_i$, the smallest one was regarded as *TRAM*.

4.3 Results and discussion

4.3.1 Soil moisture

The daily average soil moisture contents of 5, 15 and 25 cm soil profile during the soybean growing period of 2015 and 2016 are illustrated in **Fig. 4.1** with the median, the first and third quartiles, minimum and maximum values. The outliers, shown by dotted legend in boxplot of **Fig. 4.1**, reveal extreme soil moisture content. The soil moisture shows different patterns both for the treatments (two mulch treatments and one bare soil) and in crop growing years. Newspaper mulching provided the greatest soil moisture content with higher median (very close to mean) for both years among the treatments, whereas the bare soil provided the lowest seasonal moisture content by lower median in 2015. In both years, soil moisture content of bare soil fluctuated (several outliers) from extremely low to very high value, while the mulching treatments exhibited a smaller fluctuation (fewer outliers) range in soil moisture (**Fig. 4.1**). Newspaper mulching maintained the highest average seasonal soil moisture content for both crop seasons (0.31 $cm^3\ cm^{-3}$ in 2015 and 0.34 $cm^3\ cm^{-3}$ in 2016), while bare soil provided the lowest average moisture content (0.28 $cm^3\ cm^{-3}$) in 2015 and straw mulching provided the lowest average moisture content (0.32 $cm^3\ cm^{-3}$) in 2016. The bare soil also contained the lowest average moisture content (0.24 $cm^3\ cm^{-3}$ and 0.28 $cm^3\ cm^{-3}$) in 2015 (**Fig. 4.1**). The average soil moisture contents under the three treatments were higher in 2016 than in 2015. The straw mulch shows lower inter-quartile range of data in both years, indicating that the soil moisture had a high level of agreement over the soybean growing season. The mulching treatments showed smaller fluctuations (smaller outliers) of moisture contents over the 0–30 cm soil profile compared to the bare soil (several outliers) for both years. The variations of hourly soil moisture contents under the mulching treatments in response to 54.2 mm rainfall on 21 June 2015 and 55.6 mm rainfall on 9 July 2016 are illustrated in **Fig. 4.2** (a) and **Fig. 4.2** (b), respectively. Soil moisture increased during the rainfall hours and decreased afterwards, with large differences in soil moisture observed among the three depths (5, 15 and 25 cm) and three treatments for both crop years. Because of one-hour interval for soil moisture measurement, the temporal changes in soil moisture might not represent the continuous exact changes after the start of the rainfall events. We, however, focused on soil moisture reduction processes due to evaporation and downward water flow after the rainfall events. Organic mulch may have an effect to delay the infiltration of rainwater to the soil; thus soil moisture content at 5 cm depth increased faster just after rainfall event than at 15 and 25 cm depths. The hourly soil moisture reduction rate of 0–30 cm soil zone during 21–24 June (4 days) was 0.22, 0.84 and 0.88 mm h^{-1} under straw, newspaper and bare soil, respectively in response to 54.2 mm rainfall on 21 June 2015 (**Fig. 4.2** (a)). Similar reduction rate in soil moisture during 9–12 July was 0.48, 0.49 and 0.70 mm h^{-1} under straw, newspaper and bare soil, respectively in response to 55.6 mm rainfall on 9 July 2016 (**Fig. 4.2** (b)).

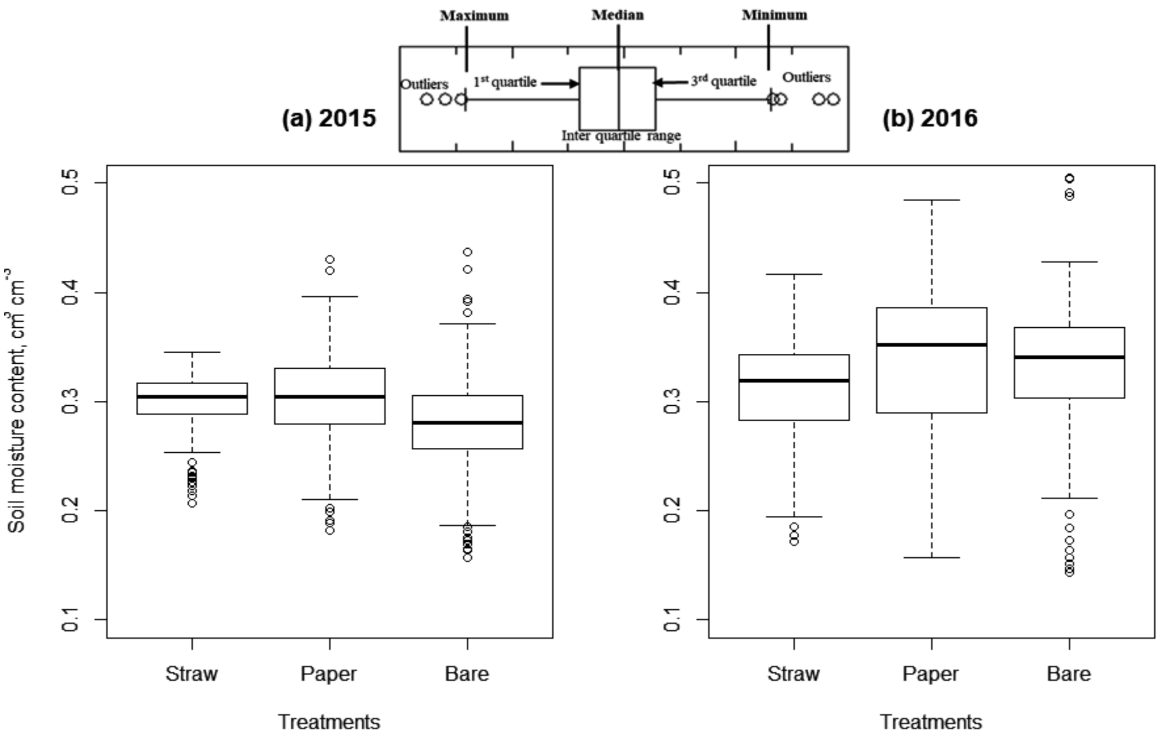

Figure 4.1 Daily average soil moisture content at 0–30 cm soil profile under three treatments (straw, newspaper and bare soil) over the soybean growing seasons of 2015 and 2016.

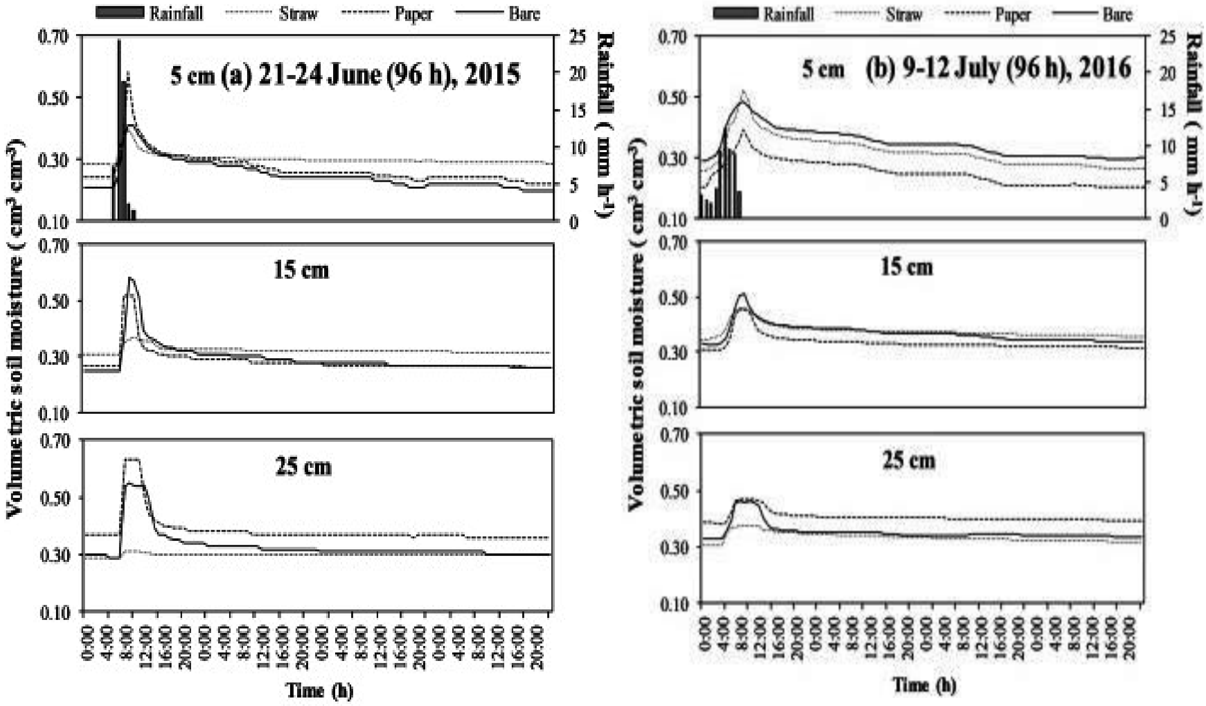

Figure 4.2 Variation of hourly soil moisture content during and after rainfall events at 5, 15 and 25 cm soil depths for three treatments (straw, newspaper and bare soil) during (a) 21–24 June (96 h) 2015 and (b) 9–12 July (96 h) 2016.

So, soil moisture reduction rate with straw and newspaper mulching decreased by 79.6 and 4.5%, respectively in 2015, and 31.4 and 30%, respectively in 2016 compared to bare soil. Straw mulching provided the lowest reduction rates of soil moisture compared to newspaper mulching and bare soil. Newspaper is a contiguous layer of mulching material and, inherently, is porous, hygroscopic, and expanding and shrinking with changes in its moisture content (Haapala et al., 2014). Newspaper mulch stored the largest quantity of soil moisture at 25 cm depth followed by straw mulch. Evaporation and drainage are the main factors to reduce soil moisture content in 0−30 cm soil profile just after rainfall events. Because of reduced evaporation rates, the straw and newspaper mulching conserved soil moisture for longer periods and resulted in higher seasonal moisture content than the bare soil. Organic mulching (e.g., straw and newspaper) improved root growth of soybean and increased root exudates (Cai et al., 2015), which might improve growth and development of soybean.

4.3.2 Soil water consumption

The cumulative soil water consumptions, *SWC*s, under three treatments are illustrated in **Fig. 4.3** for the two crop seasons of 2015 and 2016. *SWC* in the treatment plots increased over the soybean growing periods. The seasonal *SWC* under straw, newspaper and bare soil was 95, 136 and 164 mm, respectively in 2015, and 136, 126 and 158 mm, respectively in 2016. Straw mulch provided 41.8% lower *SWC* in

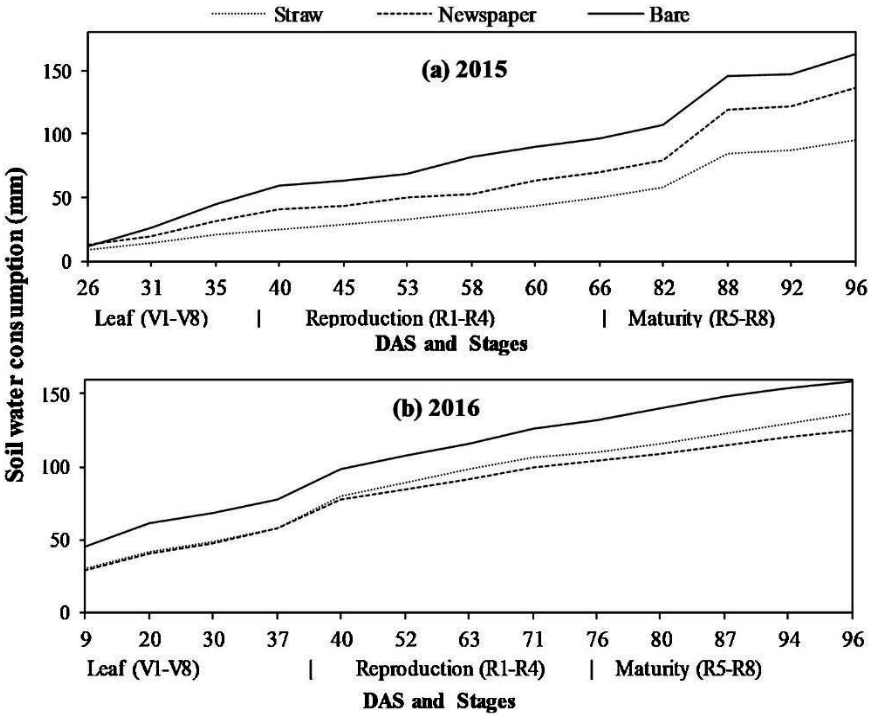

Figure 4.3 Cumulative soil water consumption from effective root zone (0–30 cm) under three treatments (straw, newspaper and bare soil) throughout soybean growing season of (a) 2015 and (b) 2016.

2015 and 13.9% lower *SWC* in 2016 than bare soil, while newspaper mulch provided 16.3 and 20.6% lower *SWC* than bare soil in 2015 and 2016, respectively. The straw and newspaper mulching suppressed evaporation from the soil and reduced *SWC*, while direct evaporation from the bare soil increased *SWC*. The bare soil released more water from the effective root zone (0–30 cm) compared to the soils under mulching.

Evaporation rate from soil that is mostly governed by soil moisture, temperature and wind speed influenced water storage in the mulch layer and water flow into soil during rainfall events (Yan et al., 2018). There were larger differences in *SWC* between 2015 and 2016 for straw and newspaper mulch treatments than for the bare soil. Perhaps, water contained in straw was readily transferred into vapor to satisfy evaporative demand from the soil and straw following energy balance at the soil surface in 2016. Newspaper mulching also showed similar behavior; saturated newspaper augmented evaporation at the mulch surface and caused water flow from soil to newspaper for further evaporation. Furthermore, newspaper degraded quickly because of frequent rainfalls in 2015 and, hence, provided relatively high *SWC*. The bare soil produced maximum surface evaporation and, consequently, provided greater *SWC* compared to the mulching treatments. The mulch materials, therefore, provided a protection on soil surface and reduced soil evaporation rate, with the consequent reduced *SWC* and increased soil moisture storage in the root zone of soybean. The reduced *SWC* under straw and newspaper mulching, therefore, can play an important role for water saving in soybean cultivation.

4.3.3 Soil temperature

The temporal variations in daily average soil temperature at three depths (5, 15 and 25 cm) in 2015 and four depths (0, 5, 15 and 25 cm) in 2016 are illustrated in **Fig. 4.4** (a) and (b), respectively. The straw and newspaper mulches exerted varying effects on soil temperature in the two crop growing seasons. Soil temperature in all cases decreased with increasing depth of soil. Daily temperatures (mean) over the soybean growth of bare soil at 5 and 25 cm depths were 26.4°C and 25.5°C, respectively in 2015, and 23.3°C and 22.7°C, respectively in 2016. The bare soil and straw mulch showed same seasonal average temperature (26.5°C) at 5 cm depth in 2015 that is 1.0°C higher than that provided by newspaper mulch. Straw mulch provided slightly higher soil temperature at 15 and 25 cm depths in 2015 than the bare soil and newspaper mulch (**Fig. 4.4** (a)). In 2016, the mean temperature at bare soil surface increased by 1.5°C during leaf formation (June–July) and reproduction stages (July–August) of soybean, while at maturity stage (August), soil surface temperature increased by 0.92°C compared to newspaper. The bare soil attained greater temperature at 5 cm depth than the soils under mulching in 2016, while soil temperature at 15 and 25 cm depths were almost similar for all three treatments (**Fig. 4.4** (b)). The average temperature difference between 5 cm and 25 cm depths was 0.84, 0.74 and 0.97°C for straw, newspaper and bare soil, respectively in 2015, and 0.21, 0.86 and 0.72°C, respectively in 2016. The bare soil was more heated by air temperature and exhibited 0–2°C temperature difference within the root

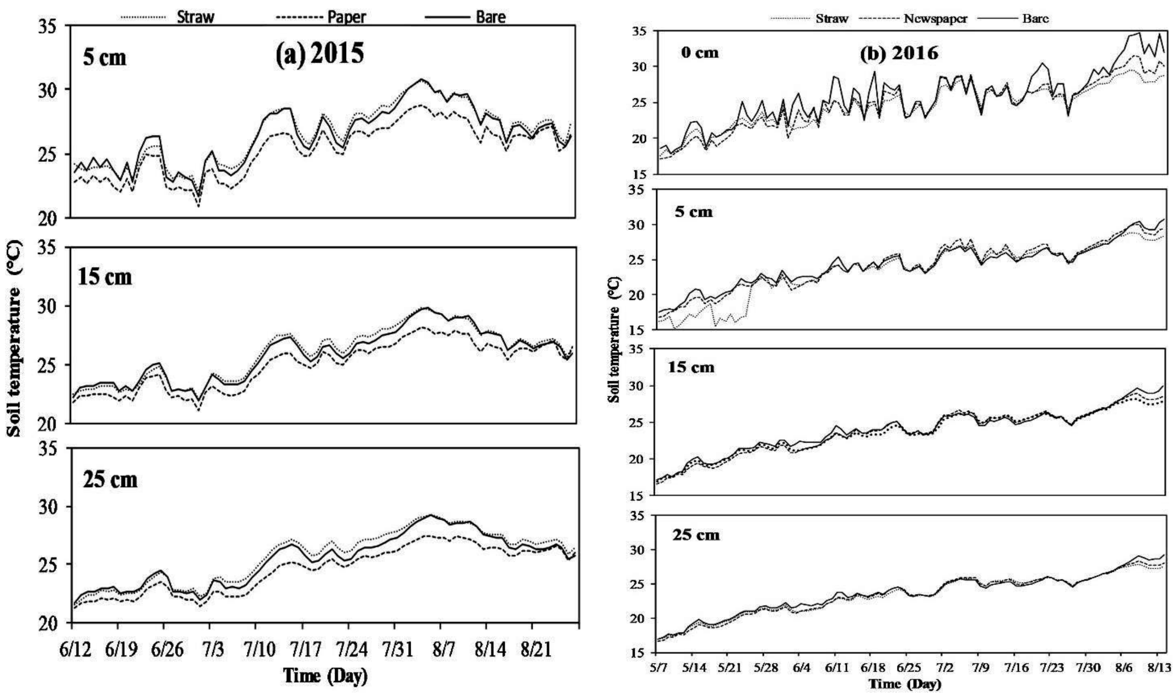

Figure 4.4 Mean daily soil temperature at 5, 15 and 25 cm depths in the experimental soybean plots under three treatments (straw, newspaper and bare soil) during the growing period of (a) 2015 and (b) 2016.

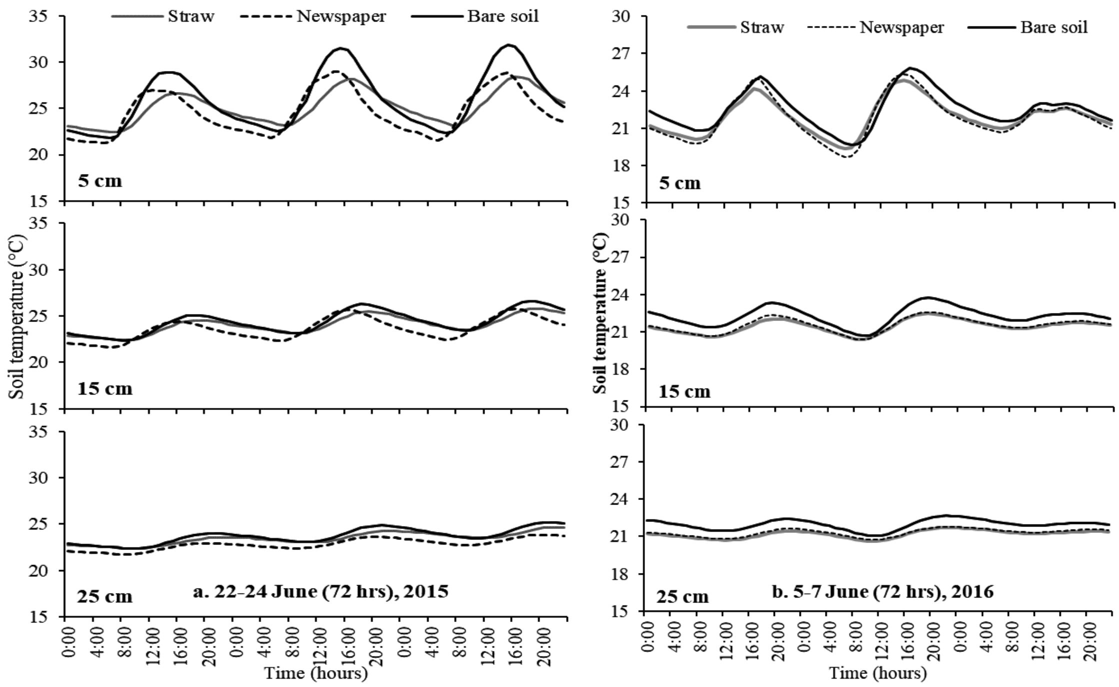

Figure 4.5 Variation of hourly soil temperature at 5 and 25 cm depths for three treatments (straw, newspaper and bare soil) during (a) 22–24 June (72 h) 2015 and (b) 5–7 July (72 h) 2016.

zone (0–30 cm). The daily fluctuations of soil temperature (up to 2°C) were higher in the upper depth (5 cm) than (0.5–1°C) in the lower depths (15 and 25 cm) of soil profile.

For better understating the effects of mulching on soil temperature during drying days after the rainfall, the hourly soil temperature variations of the three treatments at 5 and 25 cm depths during 22–24 June (72 h) in 2015 and 5–l7 June (72 h) in 2016 are illustrated in **Fig. 4.5** (a) and (b), respectively. For a 72 h variation of soil temperature, the bare soil showed higher temperature than the soils under mulching at 5 cm depth, and the newspaper mulch showed lower temperature at 25 cm depth among the three treatments. During sunlight (11 AM – 7 PM), the bare soil exhibited 2°C greater temperature than the mulching treatments at 5 cm depth, but at 25 cm depth, the difference in temperature was small (± 0.5°C). At night time, soil temperature decreased for all depths and treatments.

At crop development (June to August) and maturity (late July to August) stages, soil temperature fluctuated by 0.64°C d^{-1} (difference between maximum and minimum) under straw mulch in 2015, while at the initial stages (June), the fluctuation was 0.95°C d^{-1}. The lower fluctuation of soil temperature at crop development and maturity stages was due to reduction of solar radiation by plant canopy. Newspaper mulching provided lower soil temperature at 5 cm depth and exhibited smaller daily temperature fluctuations compared to the bare soil. Several previous studies revealed that paper mulch lowered soil temperature more than black plastic (Coolong, 2010), transparent plastic (Pessala and Hårdh, 1977), straw (Munn, 1992) and bare soil (Haapala et al., 2014). The temperature-reducing effect of the paper mulch was attributed to its lighter color that reflected incoming radiation, which, normally, was absorbed by darker surfaces like bare soil or plastic mulch (Kader et al., 2017b). Newspaper mulch created one contiguous layer of material, which lowered soil temperature after being wetted by rainfall and by reflecting solar radiation. On the other hand, heat penetration into soil from straw mulch depends on specific heat capacity and thermal conductivity of straw (thermal diffusivity). Application of straw mulch can lower the peak soil temperatures due to its high reflectivity and low thermal diffusivity, and interception of incoming radiation. These effects of organic mulching, however, depend upon soil wetness, incident radiation, rate of mulch application as well as time of the year (Sarkar and Singh, 2007).

4.3.4 Soil moisture extraction pattern

Soil moisture extraction is the amount of water loss from the effective root zone (0–30 cm) due to downward infiltration, uptake by plant roots and evaporation from soil. **Figure 4.6** illustrates soil moisture extraction pattern, *SMEP*, from the three soil layers (0–10, 10–20 and 20–30 cm) within root zone under different treatments (straw, newspaper and bare soil). The maximum soil moisture extraction occurred from 0−10 cm soil layer and minimum extraction occurred from 20−30 cm soil layer under all treatments. These observations are consistent with the findings of Chakraborty et al. (2008) and Sarkar et al. (2007). Soil moisture extraction for all three treatments in 2015 was significantly ($P \leq 0.05$) greater (≥ 45%) in 0–10 cm soil layer than in 10–20 and 20–30 cm layers; the two lower soil layers provided statistically similar soil moisture extraction (24% and 30%) (**Fig. 4.6** (a)). In 2015, almost half of the total soil moisture extracted from the root zone in all treatments was extracted from the 0−10 cm soil layer, while 10–20 and 20–30 cm soil layers showed small difference in soil moisture extraction. In 2016, the top soil layer provided the highest soil moisture extractions, which were, however, ≤ 45% for all treatments; for the lower soil layers, soil moisture extractions were approximately similar (25−26%). **Figure 4.6** (b) demonstrates that *SMEP* was more uniform within root zone in 2016 compared to that in 2015. The variation in *SMEP* over two crop years (2015 and 2016) was due to the change in soil environment by tillage operations, and soil compactions. In the study of Lenka et al. (2009), with increasing water input, soil moisture extraction occurred mostly from the upper layers due to increased root mass and availability of water for evaporation. Bandyopadhyay et al. (2003) also showed for wheat that maximum (45%) soil moisture extraction occurred from 0−15 cm soil profile, and the extraction decreased with increasing depth of soil. Water extraction was small at initial growth stage but increased at development and maturity stages of soybean because of greater amount of water uptake for physiological activities of the plants. The growth attributes of soybean (biomass, grain and seed yields) were larger in 2016 than in 2015 (**Table 4.1**), indicating deeper rooting zone and different soil moisture extraction in the three soil layers in 2016.

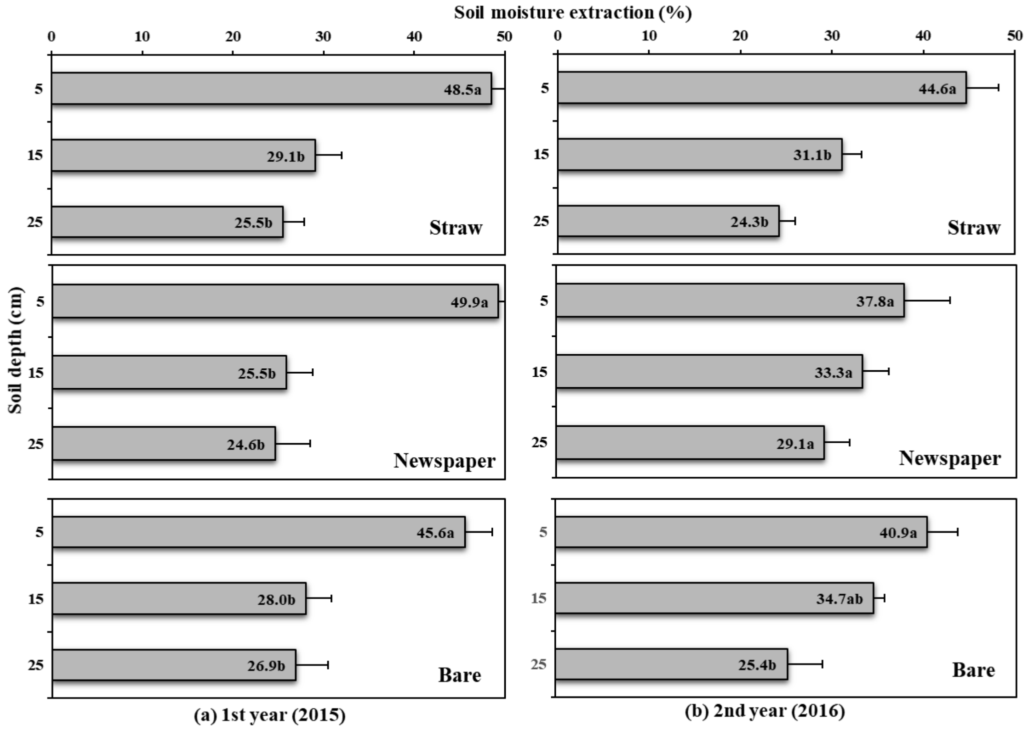

Figure 4.6 Soil moisture extraction at 5, 15 and 25 cm depths over 0–30 cm soil profile in the experimental soybean plots (a) 1st season (2015) and (b) 2nd season (2016) under three treatments (straw, newspaper and bare soil). The horizontal bar shows standard error ($n = 14$). Common letter(s) within the same treatment in a year do not differ significantly at 5% probability level analyzed by Tukey's HSD test.

4.3.5 Total readily available soil moisture

Total readily available soil moisture, *TRAM*, largely depends on *SMEP* from the 0–30 cm soil profile. The seasonal *TRAM* was the highest under bare soil (44.2 mm). As illustrated in **Fig. 4.7**, the mulching treatments provided statistically similar ($P \leq 0.05$) *TRAM* both in 2015 (32.0 to 33.5 mm) and 2016 (41.5 mm). The ratio of *TRAM* to total available water (*TAW*) for each treatment, standardized with the differences of available soil moisture among the treatments, shows similar pattern as *TRAM* (**Fig. 4.7**). Furthermore, soil moisture extractions from the top layer under straw and newspaper mulching were slightly higher than that under bare soil (**Fig. 4.6** (a)). For high rainfall amount in 2015, soil moisture extraction was larger and *TRAM* was smaller for the upper layer than for the lower layers. On the other hand, although available moistures under mulching treatments were slightly smaller in the top soil layer (**Table 3.4**) than in the lower soil layers, no noticeable difference was observed in soil moisture extraction among the three soil layers. Assuming that irrigation is to be applied, the smaller *TRAM* under the mulching treatments in 2015 implies that the amount of water for an irrigation application becomes small, and if the soil water consumption would be same, the irrigation interval would become short. This is because the irrigation interval is calculated by dividing *TRAM* by daily soil water consumption in the

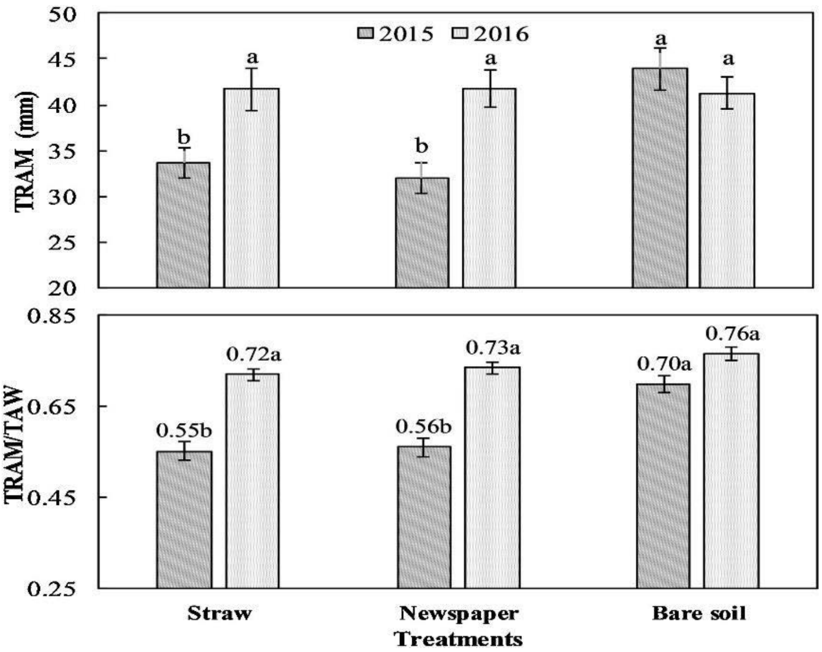

Figure 4.7 Total readily available soil moisture (*TRAM*) and the ratio of *TRAM* to total available water (*TAW*) under three treatments (straw, newspaper and bare soil) in 2015 and 2016. The vertical bar indicates standard error ($n = 14$). Common letter(s) within the same treatment in a year do not differ significantly at 5% probability level analyzed by Tukey's HSD test.

effective root zone. However, the effect of mulching on *TRAM* depends on meteorological conditions and depth of rooting zone; there was no difference in *TRAM* between straw and newspaper mulching.

4.3.6 Yields and water use efficiency of soybean

The straw and newspaper mulching helped producing higher yield of soybean compared to bare soil; the newspaper mulching provided greater yield due to higher plant height, nodulations, number of grains (pod), seeds per plant and plant biomass than straw mulching (**Table 4.1**). There were significant ($P \leq 0.05$) difference in the growth and yield attributes of soybean between 2015 and 2016, possibly, due to damaging effect of excess rainfall in 2015 crop growing period. Improved soil hydrothermal regimes (soil moisture, soil temperature, *SWC* and *SMEP*) and climatic environments (rainfall and air temperature) due to the effects of mulching enhanced soybean yields by improving crop physiology. The straw and newspaper mulching augmented soybean yield by 12–13% in 2015 and 6.6–37.2% in 2016, possible higher values of nodulations, leaf chlorophyll and biomass compared to bare soil (**Table 4.1**). Almost a similar observation of yield increase (16%) of rainfed soybean under wheat straw mulching was reported in India (Dass and Bhattacharyya, 2017). Increasing soil moisture and decreasing soil temperature enhanced 5−7% leaf chlorophyll concentration and 11−22% nodulations of soybean that attributed higher growth and yields under the two mulching treatments (**Table 4.1**).

Table 4.1 Growth and yield attributes (fresh biomass, plant height, chlorophyll, nodulation, grain, seed, fresh grain yield, green seed yield, and seed yield), soil water consumption (*SWC*) and water use efficiency (*WUE*) of soybean under three mulching treatments (straw, newspaper and bare soil) in 2015 and 2016.

Year	Treatment	Fresh biomass	Plant height	Chlorophyll	Nodulation	Grain	Seed	Fresh grain yield	Green seed yield	Seed yield	*SWC*	*WUE*
		(g plant^{-1})	(cm)	(SPAD)	(number plant^{-1})			(g plant^{-1})	(g plant^{-1})	(g m^{-2})	(mm)	(g m^{-3})
	Straw	176.1a ± 16.6	61.6b ± 2.5	47.7a ± 1.2	24.3a ± 3.0	22.8b ± 2.2	39.5b ± 4.6	72.5b ± 8.2	33.7ab ± 4.4	118.0	95.1	1.24
2015	Newspaper	222.1a ± 19.4	77.4a ± 2.7	46.7a ± 0.7	38.7a ± 4.5	30.1a ± 2.6	51.4a ± 6.2	105.7a ± 9.2	46.5a ± 5.3	162.8	136.3	1.19
	Bare soil	165.2a ± 15.5	65.5b ± 2.5	44.2a ± 1.1	21.7a ± 3.5	20.4b ± 1.6	33.2c ± 4.4	67.2b ± 6.4	29.2b ± 4.3	102.2	163.5	0.62
	Significant	NS	S	NS	NS	S	S	S	S	-	-	-
	Straw	327.7a ± 20.2	56.0b ± 1.9	41.4a ± 0.5	21.6b ± 1.6	35.9 ± 2.0	71.1 ± 4.8	139.7a ± 8.5	85.0a ± 5.4	237.0	136.2	1.74
2016	Newspaper	334.7a ±14.0	64.6a ± 2.5	41.5a ± 0.7	32.2a ± 2.9	33.8 ± 1.5	68.4 ± 4.2	130.9a ± 5.4	79.2a ± 3.8	221.0	125.5	1.76
	Bare soil	318.1a ± 25.9	63.0ab ± 2.5	38.5a ± 1.7	19.0b ± 2.1	28.0 ± 3.0	58.5 ± 5.1	115.0a ± 12.7	71.2a ± 8.8	206.0	158.1	1.30
	Significant	NS	S	NS	S	NS	NS	NS	NS	-	-	-

The values are shown as mean ± standard error; means were calculated from 10 randomly selected sample plants. Each grain (pod) contains 2-3 seeds. Means with the same smaller letter in the year are not significantly different ($P \leq 0.05$) based on Tukey's HSD test. S: significantly different and NS: not significantly different.

The effects of leaf chlorophyll and nodulations in increasing soybean yield under organic mulching were also reported by Dass and Bhattacharyya (2017), and Siczek and Lipiec (2011). Newspaper mulching, compared to other treatments, conserved higher amount of soil moisture (**Fig. 4.1**), maintained up to 2°C lower soil temperature in the root zone (**Fig. 4.2**), and provided the highest organic matter content (4.33%, 3.26%, 2.79%) (**Table 3.4**), all of which positively contributed to growth and yield attributes of soybean (**Table 4.1**). The increased organic matter from rapidly decomposed organic mulching materials (straw and newspaper) might contribute additional nutrients for soybean plants. A similar result was also reported by Kader et al. (2017b). The decreased soil temperature responded to increase soybean yield, the reason for which was clarified by Arora et al. (2011). Improved growth and yield of soybean due to organic mulching have also been reported by other investigators (Arora et al., 2011; Siczek and Lipiec, 2011).

Water use efficiency, *WUE*, of soybean was governed by *SWC* and yield of the crop (**Table 4.1**). *WUE* increased by 28.7, 32.4 and 52.3% under straw, newspaper and bare soil treatments in 2016 compared to that in 2015 (**Table 4.1**). Seed yield of soybean was higher under newspaper mulching in both crop growing years than under other two treatments, but the lower *SWC* under straw mulching compared to the other treatments in 2015 significantly ($P \leq 0.05$) improved *WUE*. The two mulching treatments improved *WUE* over that in bare soil; this observation was similar to that of Zheng et al. (2017) and Steinmetz et al. (2016). Among the three treatments, straw and newspaper much provided the highest *WUE* in 2015 and 2016, respectively (**Table 4.1**). The straw mulch provided 40.2 and 25.2% greater *WUE* in 2015 and 2016, respectively compared to the bare soil, while the newspaper mulch provided 47.8 and 26.3% greater *WUE* in 2015 and 2016, respectively than the bare soil.

4.4 Conclusions

Two years' (2015 and 2016) field experiments with soybean cultivation under rainfed condition in central Japan revealed that rice straw and newspaper mulching enhanced soil moisture and water use efficiency and lowered temperature as well as soil water consumption compared to bare soil. Mulching exerted greater effects on seasonal soil moisture compared to bare soil, and reduced soil moisture fluctuations within the crop root zone. It lowered soil temperature by 2°C at 5 cm depth and 0.5–1.0°C at 15–25 cm depths compared to bare soil during the two soybean growing seasons. Compared to bare soil, straw mulching decreased *SWC* by 41.8% in 2015 and 13.9% in 2016; the corresponding decreased in *SWC* for newspaper mulching was 16.6% and 20.6%. Soil moisture extraction was the highest from 0 to 10 cm depth (≥ 38%) followed by 10−20 cm (26−35%) and 20−30 cm (24−29%) under the three treatments in both soybean growing seasons. Total readily available soil moisture varied due to different root distributions and soil characteristics. Water use efficiency, *WUE*, increased by 25–47% under mulching compared to bare soil. Plant biomass, plant height, leaf chlorophyll, nodulations, grain and seed yields as well as *WUE* of rainfed soybean increased significantly ($P \leq 0.05$) under the mulching treatments compared to bare soil. Straw and newspaper mulching increased soybean yield by 12–13% and 6.6–37.2%, respectively compared to bare soil; the increase was, mainly, due to 11−44% increase in nodulation, 5−7% increase in leaf chlorophyll and 4−34% increase in plant biomass under mulching in two cropping seasons. Although both the organic mulches provided good results, newspaper mulch resulted lower temperature, reduced *SWC*, greater yield and increase *WUE*. Therefore, newspaper would be an alternative option to straw materials for modifying soil hydrothermal regimes in rainfed soybean cultivation.

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CHAPTER 5

Effects of plastic-hole mulch on effective rainfall and readily available soil moisture

5.1 Introduction

The use of plastic film in agriculture, known as plasticulture (Kasirajan and Ngouajio, 2012), accelerates crop growth and augments crop yield (Tiwari et al., 2003; Zhao et al., 2009) by improving soil water retention (Ghosh et al., 2006) and controlling soil temperature (Ramakrishna et al., 2006). As the short-term effects on soil conditions (control on temperature and moisture regimes), plastic mulching provides higher product yield and quality, and hence, higher economic value for farmers (López-López et al., 2015). Although plastic mulching entails greater initial cost, increased income from earlier harvests, higher yields and better-quality product offset the cost to create an economic advantage for using this mulching (Steinmetz et al., 2016). The pattern of plastic mulching to be used in a particular situation depends on local climatic conditions (Wang et al., 2015) and cost effectiveness. The types of plastic mulching materials and techniques of their establishment remarkably affect soil water transformation and aerodynamic properties (Yang et al., 2015). Several modifications of plastic mulching are now in practice, especially for dry land, such as water-osmotic plastic film (Yao, 1998) for mulching two subsequent crops with the same plastic film and double-line ridge plastic film (Yin et al., 2016) for improving water use efficiency. The other patterns of plastic mulching, such as flat plastic cover (Zhang et al., 2015), ridge shape (Wang et al., 2016; Xiukang et al., 2015) and combination of ridge-furrow (Xiukang et al., 2015; Zhao et al., 2014), are also commonly practiced in agriculture. A relatively newly modified plastic mulching, called plastic-hole mulching, has good prospect under various crop management practices to increase productivity and rainfall use efficiency in rainfed farming systems in dry land environments.

Mulching affects available soil moisture (Awe et al., 2014) and soil temperature (Khan et al., 1998), both of which influence plant growth and yield. Plastic mulching affects crop microclimate by modifying radiation budget of the soil surface and reducing soil water loss (Filipović et al., 2016). Soil moisture extraction pattern, *SMEP*, of soybean plants depends on water management practices and root characteristics (Irmak et al., 2014). Therefore, plastic mulching has the potential to boost soybean growth by increasing available soil moisture and reducing soil temperature in the root zone during hot summer. In flat plastic mulching, a non-perforated plastic film covers a farmland and controls soil temperature and moisture regimes while protecting the soil from direct infiltration of rainfall. In contrast, a flat plastic-hole mulching has the provision to allow infiltration of rainfall and aeration into soil. The plastic-hole mulch with uniform holes has potential to inhibit evaporation from soil surface and permit rainfall infiltration and aeration into the soil through the holes. It is highly possible that this mulching would increase available soil moisture and alter temperature regime in the root zone soil. However, to our knowledge, there are no published records of in-depth investigation of these issues of plastic-hole mulching until now. It is envisaged that application of plastic-hole mulching would modify the water-uptake status of soybean like most other crops. In order to explore the potential of this modified mulching pattern, over the other mulching types, to enhance soil moisture availability by utilizing rainfall and to control soil temperature needs field investigation. Therefore, we evaluated and compared the effects of plastic-hole mulching, flat plastic mulching and no mulching (bare soil) for rainwater utilization for soybean cultivation. The specific objectives of the study were to evaluate and compare soil temperature, total readily available soil moisture and soil moisture extraction pattern of the three mulching treatments under soybean cultivation in a field experiment.

5.2 Materials and methods

5.2.1 Treatments

In this chapter, the effects of plastic-hole (PH), plastic mulch (P) and bare soil treatments were evaluated from the field experiment in 2015.

5.2.2 Effective rainfall

The effective rainfall (*ER*), defined as the amount of rainfall that can be utilized by plants within the root zone, was estimated from the summation of soil moisture increase in 0–10, 10–20 and 20–30 cm soil layers corresponding to each rainfall event. *ER* (mm) for each rainfall event was calculated by

$$ER = \sum_{i=1}^{3} \left(\theta_{24h,i} - \theta_{0h,i} \right) \cdot d_i \tag{5.1}$$

where θ is volumetric soil moisture content ($cm^3\ cm^{-3}$), d is thickness of a soil layer (mm), subscript i is the number of layers of a soil, subscript 24 h implies 24 hours after the rainfall event has receded, and subscript 0 h implies just before the rainfall event has begun. Moreover, quantification of mulching effects were analyzed by total available soil water (*TAW*), soil moisture extraction pattern (*SMEP*) and total readily available soil moisture (*TRAM*) which have been described in the previous chapter 4 (**section 4.2.3**).

5.3 Results and discussion

5.3.1 Soil temperature

The P and PH treatments reduced soil temperature by up to 2°C within 5 cm soil profile (**Fig. 5.1**) compared to the bare treatment throughout the soybean growing period. Soil temperature at 15 and 25 cm depths did not differ considerably among the three mulching treatments. The silver-color plastic film mulch had high reflectivity, and low absorptivity and transmissivity.

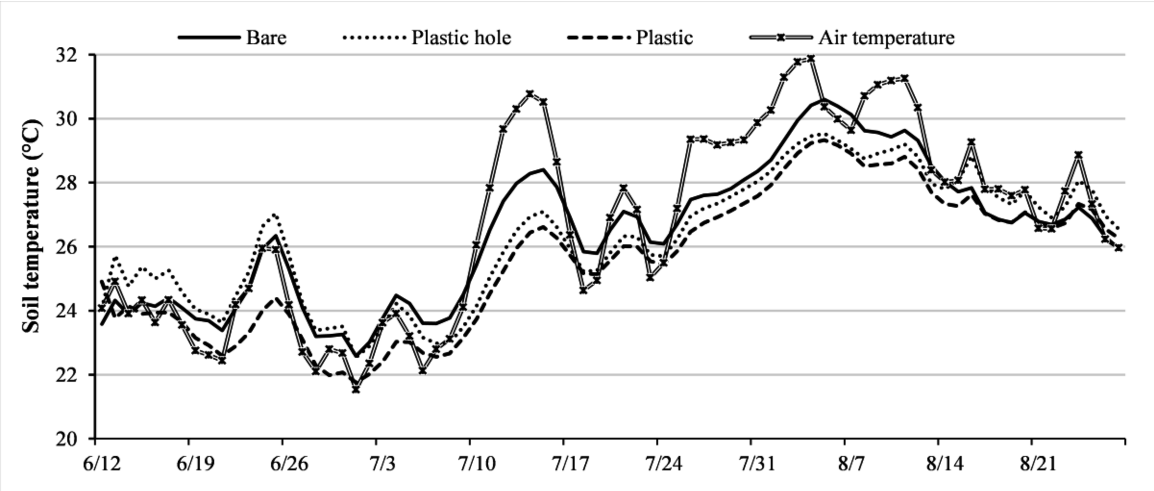

Figure 5.1 Mean daily soil temperature at 5 cm depth in the experimental soybean plot under three different mulching treatments along with air temperature during the growing period.

Consequently, it reduced soil temperature substantially that was also reported by Lamont (1993). The daily mean soil temperature at 5 cm depth was the lowest (25.9 ± 2.2°C) under the P treatment and highest (26.4 ± 2.2°C) under the bare soil during the soybean growing period; the daily mean air temperature during the same period was 26.7 ± 5.2°C. The plastic-hole mulching treatment, which covered most of the land area and only the areas of the holes remained bare/open, provided soil temperature as 26.3 ± 2.0°C. Although soil temperature in the P and PH treatments remained relatively uniform over time, that in the bare greatly fluctuated throughout the growing season. The reason why soil temperature fluctuations were different between the mulching and bare treatments, was the mechanism of energy balance at soil surface that involved the incoming solar radiation, outgoing soil heat fluxes, and sensible and latent heat fluxes (Mahrer, 1991; Komariah et al., 2011). The plastic-hole mulching altered soil temperature, which positively affected growth attributes and yield of soybean. Sekhon et al. (2005) also reported improved growth and yield of soybean under lower soil temperature maintained with mulching.

5.3.2 Effective rainfall

Total rainfall during the soybean growing period (15 May to 27 August) was 811.8 mm (**Fig. 3.2**). Of the rainfall events during this period, twelve events were major and the others were minor; three rainfall events were high: 98.2 mm on 26 June, 97.8 mm on 1 July and 93.2 mm on 17 August. The twelve rainfall events providing a total amount of 520 mm were taken into account to determine the total effective rainfall, *ER*, during the growing season of soybean. The lateral inflows of water into each treatment were considered same and hence ignored for simplicity of calculation. Most of the rainfall events resulted in the highest *ER* values in the bare treatment. Consequently, this treatment provided

Table 5.1 Effective rainfall obtained in the 0–30 cm of soil profile in the experimental soybean plots under three different mulching treatments.

Rainfall event	Date	Rainfall (mm)	Effective rainfall (mm) under		
			Plastic	Plastic hole	Bare
1	12-Jun	9.2	4.9	4.9	6.0
2	21-Jun	54.0	5.7	8.5	15.0
3	26-Jun	98.2	10.3	20.0	18.0
4	1-Jul	97.8	0.7	5.6	15.1
5	9-Jul	14.4	1.4	2.5	4.0
6	16-Jul	53.8	2.6	12.2	13.3
7	22-Jul	27.0	6.5	14.7	9.0
8	7-Aug	13.6	8.8	6.0	6.0
9	13-Aug	16.6	12.0	10.9	11.0
10	17-Aug	93.2	24.6	31.5	38.3
11	21-Aug	18.2	0.6	0.5	1.0
12	25-Aug	24.0	6.6	13.8	15.9
	Total	520.0	83.6	131.0	152.6
			16.3*	25.3*	29.6*

* The ratio of total effective rainfall to total rainfall (%)

the highest total *ER* of 152.6 mm (**Table 5.1**) in the 0–30 cm soil profile during the soybean growing period. This *ER* (152.6 mm) corresponded to 29.6% of the total rainfall (520 mm).

During the same time period, the PH and P treatments provided a total *ER* of 131.0 mm and 83.6 mm, respectively, which, correspondingly, constituted 25.3% and 16.3% of the total rainfall. In terms of generating effective rainfall, the bare (B) and PH treatments did not differ significantly (P = 0.16), whereas the B and P treatments differed significantly (P = 0.007) at 5% probability level. Rainfall could not infiltrate directly through the plastic mulching (without holes) as it did through the bare soil. Therefore, the bare treatment provided the highest *ER*. In the PH treatment, partial holes in the plastic film functioned like the bare treatment and allowed the rainfall to infiltrate directly. However, the covered portion restricted infiltration of rainfall and behaved like the P treatment. Therefore, *ER* of the PH treatment was a little lower than that of the bare treatment, but was higher than the P treatment.

5.3.3 Soil moisture extraction pattern

The soil moisture extraction pattern, *SMEP*, depicts the distribution (ratio) of soil moisture consumption by plants in the soil layers. **Figure 5.2** illustrates *SMEP*s in the 0–30 cm soil profile during the seven least moisture (drought) events over the soybean-growing period for the three mulching treatments. The soil-moisture extraction ratio was the highest in the upper most (0–10 cm) soil layer and lowest in the deepest (20–30 cm) soil layer for the bare treatment. This result is fully consistent with the findings of Chakraborty et al. (2008) and Sarkar et al. (2008). The plastic mulching altered *SMEP*; the highest soil moisture extraction was in the 10–20 cm soil layer. For the top layer (0–10 cm), soil moisture extraction was the highest under the bare treatment (42.9%) followed by PH treatment (38.6%) and P treatment (34.7%), implying that the mulching treatments reduced water extraction in the surface layer of the soil. The restriction of evaporation from soil surface by the mulching drastically inhibited upward soil water flux, which eventually reduced soil water extraction in the mulched soil. While the P treatment completely restricted soil surface evaporation, the PH treatment only partially inhibited it. In 10–20 cm soil layer, the P treatment showed greater soil moisture extraction ratio (43.07%) compared to the PH and B treatments since the soil surface under the P treatment was completely covered and, consequently, more water uptake occurred from the 10–20 cm (middle) layer for the development stages of soybean plants. Djaman and Irmak (2012) also reported influence of soil surface evaporation on the variation of soil moisture extraction within soil profile. In the study of Lenka et al. (2009), with increasing water input, soil moisture extraction occurred mostly from the upper layers due to increased root mass and availability of water for evaporation in the upper soil layers. However, the soil and crop types may be the possible factors to change soil moisture extraction patterns under mulched conditions. Farré and Faci (2006) stated that maize extracted most of the soil moisture from 0–50 cm soil profile while sorghum extracted soil moisture from the deeper layers (50–100 cm) at smaller soil water contents. Bandyopadhyay and Mallick (2003) showed that, for wheat, maximum 45% soil moisture extraction occurred in 0–15 cm soil profile, and the extraction decreased with the depth of soil. In our study, the soil moisture extraction ratio in the deepest layer (20–30 cm) was the greatest under the PH treatment (30.5%) followed by the P treatment (22.7%) and B treatment (15.8%), obviously indicating that the mulching treatments augmented water extraction from the deeper soil layers. The *SMEP* revealed that, for the bare treatment, soil moisture was consumed mostly from the top layer, while for the P and PH treatments the consumption was from both the upper and deeper soil layers.

5.3.4 Total readily available soil moisture

Both *TAW* and *SMEP* regulated readily available moisture in the soil. The bare treatment provided the lowest total readily available soil moisture, *TRAM* (48.0 mm), implying that, among the three mulching treatments, the B treatment needed irrigation first. The P treatment provided the maximum *TRAM* (57.3 mm; **Fig. 5.3** (a)) since *TAW* was the largest (25.0 mm; **Table 3.4**) in the 10–20 cm soil layer. The soil-moisture extraction ratio in this layer was the greatest among the three soil layers. The *TAW* under the three treatments was almost the same, 63–68 mm (**Table 3.4**), but the *TRAM* was considerably different. The *TRAMs* under the P and PH treatments (57.3 and 54.0 mm) were greater than the *TRAM* (48.0 mm) under the bare treatment. $TRAM_i$ was calculated from the $SMEP_i$ events by selecting its lowest value from the three soil layers under each treatment. The mean of the *TRAM*s is illustrated in **Fig. 5.3** (a).

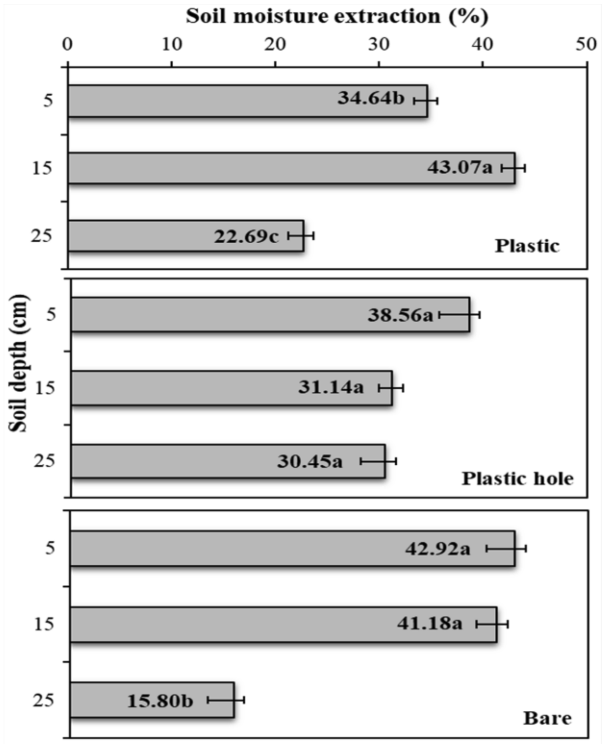

Figure 5.2 Soil moisture extraction at 5, 15 and 25 cm depths over 0–30 cm soil profile in the experimental soybean plots under three different mulching treatments. The horizontal bar shows the standard error (n = 7). Common letter(s) within the same treatment do not differ significantly at 5% probability level analyzed by Tukey's test.

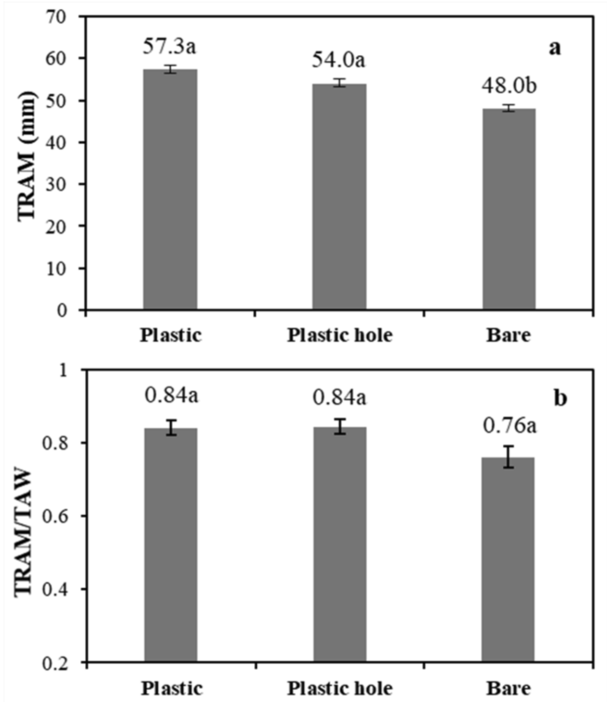

Figure 5.3 (a) Total readily available soil moisture (*TRAM*) and (b**)** ratio of total readily available soil moisture (*TRAM*) to total available soil water (*TAW*) under three different mulching treatments. The vertical bar indicates standard error (n = 7). Common letter(s) within the same treatment do not differ significantly at 5% probability level analyzed by Tukey's test.

The increased *TRAM* under the plastic and plastic-hole treatments influenced the soybean plants, which easily uptook soil water over a greater range compared to the bare soil.

A new index, defined by the ratio of *TRAM* to *TAW*, depicts the availability of *TAW* as evapotranspiration; the characteristics of *SMEP* directly influenced the evapotranspiration. The values of this index under the two mulching treatments (*P* and *PH*) were the same (0.84) but higher than that for the bare treatment (0.76) (**Fig. 5.3** (b)), implying that the *SMEP* in the crop root zone became flat due to the effects of mulching. Consequently, the P and PH treatments could effectively utilize 84% of *TAW* for satisfying evapotranspiration need, whereas the bare treatment utilized 76% of *TAW*. Thus, application of mulching increased *TRAM* compared to no mulching by the reason why the ratio of *TRAM* to *TAW* increased without changing the soil physical properties; this role of mulching is very crucial in water-saving agriculture.

5.3.5 Soybean growth and yield

The PH and P treatments substantially augmented plant height, grains per plant, total biomass and yield of soybean (**Table 5.2**). Parker and Meyer (1996) also reported 15−18% increase of soybean seed yield under plastic film mulching compared to the bare soil. Although total weed biomass was the maximum under the bare treatment (8.7 kg), the P and PH treatments also provided some weed biomass from the surrounding of the soybean growing plots. The PH treatment produced the tallest plant height and maximum total biomass, but the minimum weed biomass, thus providing a condition for increased seed yield of soybean. Consequently, the plant height, nodulation and yield of soybean increased under the mulching treatments. These results were in conformity with the findings of Siczek et al. (2015). Sinkevičienė et al. (2009), however, reported obtaining varying (increasing or decreasing) crop yield under different mulching treatments, while Singh et al. (2007) always obtained increased yield and improved yield quality under mulching.

Leaf chlorophyll content (SPAD value) of soybean at harvest was almost similar for the three mulching treatments, but the number of nodulation was more under the PH treatment compared to the bare soil. The effects of mulching on nodulation boosted up seed yield of soybean that was also found by Siczek and Lipiec (2011). The PH treatment produced the maximum seed yield of soybean (43 g plant^{-1}). The variation in soil temperature, effective rainfall and total readily available soil moisture at the root zone in different treatments caused the observed variations in soybean yield among the treatments.

Table 5.2 Comparisons of growth attributes of soybean obtained under three different mulching treatments.

Analyzed parameter	Plastic	Plastic-hole	Bare	Significance
Total plant height (cm)	79.0 ± 3.2a	83.8 ± 3.6a	65.5 ± 2.5b	S
Total biomass (g)	226.9 ± 27.4b	291.9 ± 38.7a	165.2 ± 15.5b	S
No. of grain per plant	26.3 ± 2.4	25.3 ± 2.5	20.4 ± 1.6	NS
Grain yield per plant (g)	72.4 ± 8.2	79.6 ± 7.5	67.2 ± 6.4	NS
No. of seed per plant	42.3 ± 4.6	43.0 ± 4.1	33.2 ± 4.4	NS
Seed yield per plant (g)	34.6 ± 5.9	37.1 ± 4.8	29.2 ± 4.3	NS
Nodulation number per plant	18.0 ± 1.7b	31.8 ± 2.3a	22.0 ± 3.5ab	S
Chlorophyll (SPAD value)	48.2 ± 1.2	44.6 ± 0.6	47.2 ± 1.1	NS
Weed biomass (kg)	1.8	1.3	3.7	-

The values are shown as mean ± standard error; means were calculated from 10 randomly selected samples. S: significantly different, NS: not significantly different. The lower-case letters within each line indicate significant differences ($P < 0.05$) by Tukey's HSD test.

5.4 Conclusions

The silver-color plastic mulching treatments, by reducing soil temperature, created a better environment for soybean growth under high air temperature during hot summer in Japan. The plastic-hole mulching augmented effective rainfall by 9% of the total rainfall compared to the plastic mulching (without holes). Both mulching treatments altered soil moisture extraction pattern, which became relatively uniform in the root zone of soybean. As a result, ratio of total readily available soil moisture (*TRAM*) to total available soil water (*TAW*) became greater under the mulching treatments compared to the bare treatment. The greater *TRAM* to *TAW* ratio is a manifestation of augmented available soil moisture within the root zone without any change of soil physical properties. The application of mulching also boosted up plant height, total biomass and seed yields of soybean compared to the bare treatment. Especially, the seed yield of soybean increased by 6.7% under plastic-hole mulching compared to the plastic mulching (without holes). The results of this study thus conclude that the plastic-hole mulching is a good option for effective utilization of rainfall, increasing soil moisture extraction ratio in the deeper soil layers and increasing total readily available soil moisture for plant growth. However, more research is required on plastic-hole mulching to document physio-chemical strengths, technique details and long-term sustainability of this mulching. We strongly recommend the plastic-hole mulching for farmers in the arid and semi-arid regions for effective utilization of rainfall for crop production in order to save their scarce water resources.

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CHAPTER 6

Effects of coloured plastic mulch on soil hydrothermal characteristics and soybean productivity

6.1 Introduction

Plastic film mulching is an effective technique for modification of soil microclimate in rainfed agriculture by reducing evaporation, retaining soil moisture and altering soil temperature (Kader et al., 2017a; Zheng et al., 2017). Although organic mulch has some advantages over plastic mulch (e.g., it adds organic matter to soil after decomposition), its price is increasing over time since it is also used as feed for livestock. As a result, plastic film mulches being reasonably cheap, long-lasting and rapid result provider, are becoming popular. These mulches have a number of advantageous effects in solarization, early harvesting, insect and weed control, crop yield and water use efficiency compared to organic mulch (Steinmetz et al., 2016). In recent years, China, Japan and South Korea have become the greatest users of plastic film mulch; their usages account for 80% of worldwide use (Ihuoma and Madramootoo, 2017). However, there are several options associated with selection of plastic film mulch, such as color of film, method of application (ridge-furrow, flat), thickness of mulch (one layer, two layers) and perforation (size of hole inside the film) (Kader et al., 2017a). Of these options, the color of the plastic film is a vital factor that can regulate thermal regime of a soil by altering its temperature.

The colors of the film influence crop yield by providing different soil temperature regimes. An appropriate selection of the color of plastic film is therefore important to achieve maximum benefit of mulching. Although, many natural factors (e.g., weather, crop and climatic regions) affect the effectiveness of mulching, the color(s) of plastic film that may be suitable in our study area has not been studied yet. Suitable environment with optimum root zone temperature is needed for the production of superior quality soybean. The extent of modification of soil temperature by different colors of plastic films and their effects on soybean growth are crucial for proper cultivation of the crop in regions like central Japan. Therefore, we investigate the comparative effects of three popular colors (black, silver and transparent) of plastic film mulches and a bare soil (no-mulch) on soil temperature and soil water consumption, along with their impacts on growth, yield and water productivity of rainfed soybean.

6.2 Materials and methods

6.2.1 Treatments

In this chapter, four treatments: three colored impervious plastic film mulches and a bare soil (no-mulch) were investigated during 26 April – 14 August in 2016 under rainfed soybean field. The colored mulches were black plastic mulching (BPM), silver plastic mulching (SPM) and transparent plastic mulching (TPM). The thickness of the film of each color was 20 µm, and only one layer plastic film was used for each mulch plot.

6.2.2 Analysis

We estimated soil water consumption (**section 4.2.2**; equation **4.1**), water productivity (**section 3.7**; equation **3.1**) and soil heat accumulation. Accumulation of heat in soil is estimated by arithmetic summation of daily mean temperature above a base temperature (Subrahmaniyan et al., 2018) and expressed as degree days (°D) or growing degree days (GDDs). The base temperature (T_{base}) in estimating heat accumulation is the minimum temperature below which development of a crop does not progress (McMaster and Wilhelm, 1997). The accumulated heat of each treatment was computed at 5, 15 and 25 cm depths above the threshold temperature following Ngouajio and Ernest (2005):

$$Heat\ accumulation\ (°\mathrm{D}) = \sum_{k=1}^{N} \left(\frac{1}{2} \times (T_{\text{Max}} + T_{\text{Min}}) - T_{\text{base}} \right) \quad (6.1)$$

where T_{Max} and T_{Min} is the daily maximum and minimum soil temperature, respectively at each depth, N is the number of days of growth period, and k is the day. Based on previous findings (e.g., Ngouajio and Ernest, 2005; Subrahmaniyan et al., 2018), we considered T_{base} as 10°C for the soybean growing season in our study. Cumulative heat accumulation in the root zone (0–30 cm) was calculated by summing up the heat accumulation at 5, 15 and 25 cm depths during the growing period of soybean. Heat use efficiency (*HUE*) was determined by the ratio of seed yield of soybean per square meter to the cumulative heat accumulation in the root zone.

6.3 Results and discussion

6.3.1 Air and soil surface temperatures

Figure 6.1 illustrates the relationship between daily soil surface temperature (0 cm depth) and air temperature under four treatments at three growth stages of soybean. There was a positive correlation between soil surface temperature and air temperature under the bare treatment. TPM showed the maximum fluctuation of daily mean temperature, especially at the vegetative stage, and hence did not provide any correlation (R^2 = 0.03) between the two temperature sets. Bare soil provided the strongest relationship (R^2 = 0.85) between these temperature sets. The color of the plastic films greatly influenced soil surface temperature beneath the mulches (**Fig. 6.1**). Among the mulching plots, SPM and BPM, compared to TPM, provided stronger relationships (R^2 = 0.47 and 0.33, respectively) between soil surface temperature and air temperature. For the TPM treatment, soil surface temperature fluctuated more at vegetative stage than at maturity stage since the soybean leaves largely prevented incident solar radiation from reaching the soil surface at the vegetative stage. TPM partly reflected and mostly transmitted the incident radiation that warmed up inside of the transparent film and, consequently, raised temperature at the soil surface. Due to the dark surface, BPM had low reflectance. In the reproductive

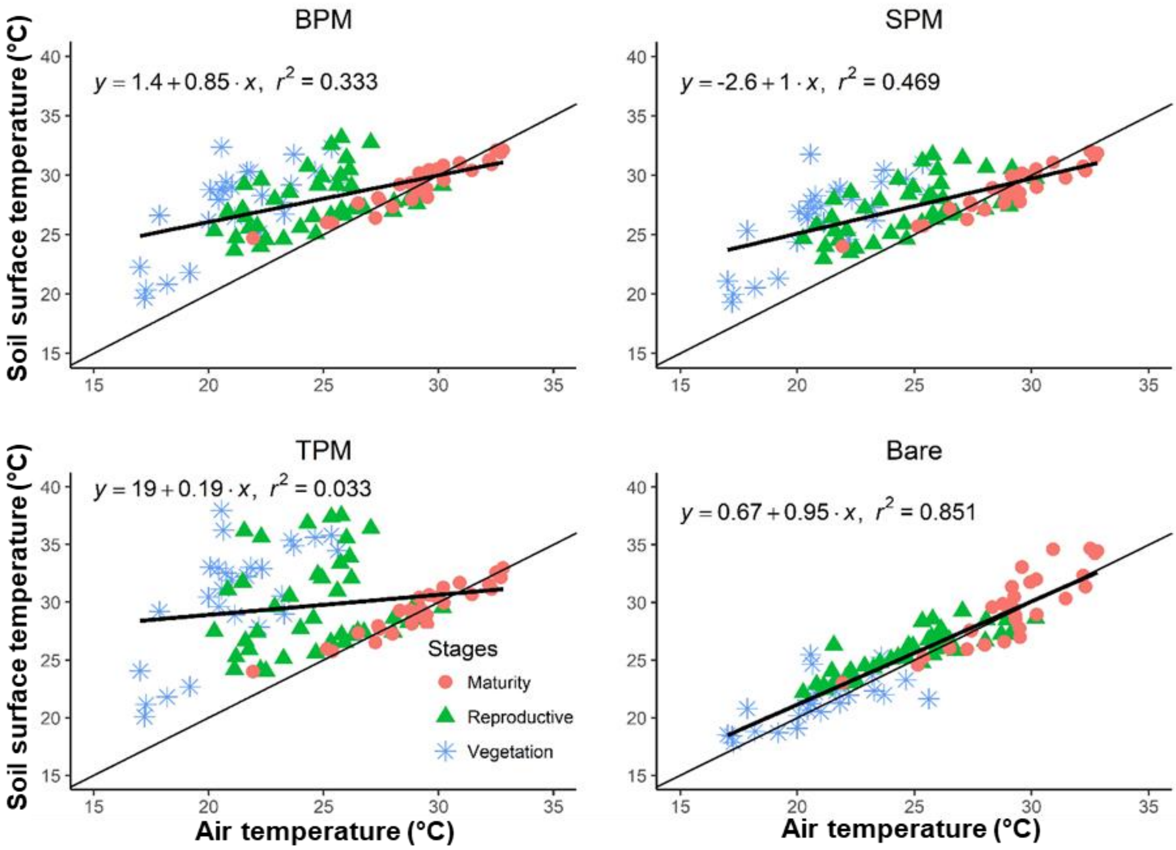

Figure 6.1 Variation of soil surface temperature as a function of air temperature and functional relationship between these two temperature-sets at different growth stages of soybean cultivation under three colored plastic film mulches and bare soil.

and maturity stages of soybean, this mulch absorbed more heat than SPM and increased soil temperature. The daily average temperature of the soil surface in the bare treatment was close to the daily average air temperature (R^2 = 0.85) due to direct incidence of incoming solar radiation. The reflection, absorption and transmission capacities of the colored plastic films were different based on their albedo, insulation and transparency.

6.3.2 Soil temperature

Temperature at different depths below soil surface was mainly controlled by the incident solar radiation that varied within the treatments. **Figure 6.2** illustrates temporal variation of daily mean soil temperature at 0, 5, 15 and 25 cm depths under four different treatments. Soil temperature increased progressively during the growing season of soybean in each treatment, with the highest temperature at soil surface (0 cm depth) and lower temperature at deeper depths (0–25 cm). TPM augmented topsoil temperature by 4–8°C compared to BPM and SPM. At the maturity stage (late July–August) of the crop, the temperature difference was only 1°C among the three plastic mulch treatments (**Fig. 6.2**). Boosting up soil temperature at early growth stages of soybean is crucial, since soil warming stimulates uniform plant growth and development (Pramanik et al., 2015). The average daily maximum, minimum and mean soil temperatures at 5, 15 and 25 cm depths, as observed in the experiment, were significantly ($P < 0.05$) higher in the soils with plastic film mulches compared to bare soil (**Table 6.1**). Similar findings were also reported when colored plastic mulching was used for various rainfall intensities and other plants like potato (Ibarra-Jiménez et al., 2011). In our experiment, colored plastic mulching raised soil temperature by 3–7°C during vegetative stage (May–June) at 5, 15 and 25 cm depths relative to bare soil. The bare soil showed higher daily fluctuations (6–17°C) between maximum and minimum soil temperatures at vegetative stage. At maturity stage (July–August), the colored plastic mulching showed only 1–2°C increase in temperature, with smaller (4–8°C) fluctuations at 15 and 25 cm depths. BPM raised temperature at deeper soil layers, while TPM and SPM minimized fluctuation of soil temperature in the deeper layers. Thus, the color of the plastic films affected soil surface temperature and, ultimately, altered soil temperature at deeper layers that was also reported by Lamont (1993).

The colored plastic mulching raised maximum, minimum and mean soil temperatures; the highest temperature was obtained under BPM at different soil depths (**Fig. 6.2**, **Table 6.1**). These results are consistent with Tarara (2000) and Canul-Tun et al. (2017). TPM generated higher temperature with greater fluctuations at soil surface (**Fig. 6.2**) since most of the incident solar radiation transmitted into the soil surface through the transparent film. In addition, the colors of plastic mulching raised soil temperature by suppressing latent heat through reduction of evaporation (Filipović et al., 2016). BPM, having high absorbing and low transmitting capacity of sunlight, raised temperature by 3–4°C at lower soil depths compared to SPM. BPM provided the highest soil temperature (25–31°C) among the three colored plastic mulching treatments at 5, 15 and 25 cm soil layers, while SPM provided the lowest soil temperature (23–28°C) over the entire growing period of soybean. There was a temperature difference of 2–3°C between BPM and TPM within each soil layer over the soybean growing season. The colored plastic mulching generally raised soil temperature compared to bare soil (Canul-Tun et al., 2017; Ibarra-Jiménez et al., 2011; Pramanik et al., 2015). BPM raised root zone temperature by 6.4, 6.2 and 5.9°C at 5, 15 and 25 cm soil depths, respectively, while with TPM, the corresponding increase in temperature was 5.9, 5.4 and 4.4°C. Plastic mulching greatly reduced fluctuation of daily maximum and minimum soil temperatures compared to bare soil (Kader et al., 2017b). The increase in soil tempermature under the mulching treatments at reproductive stages of soybean was due to the greater foliage area of the crop; the foliare area prevented a large part of incident solar radiation from reaching the mulch/soil surface.

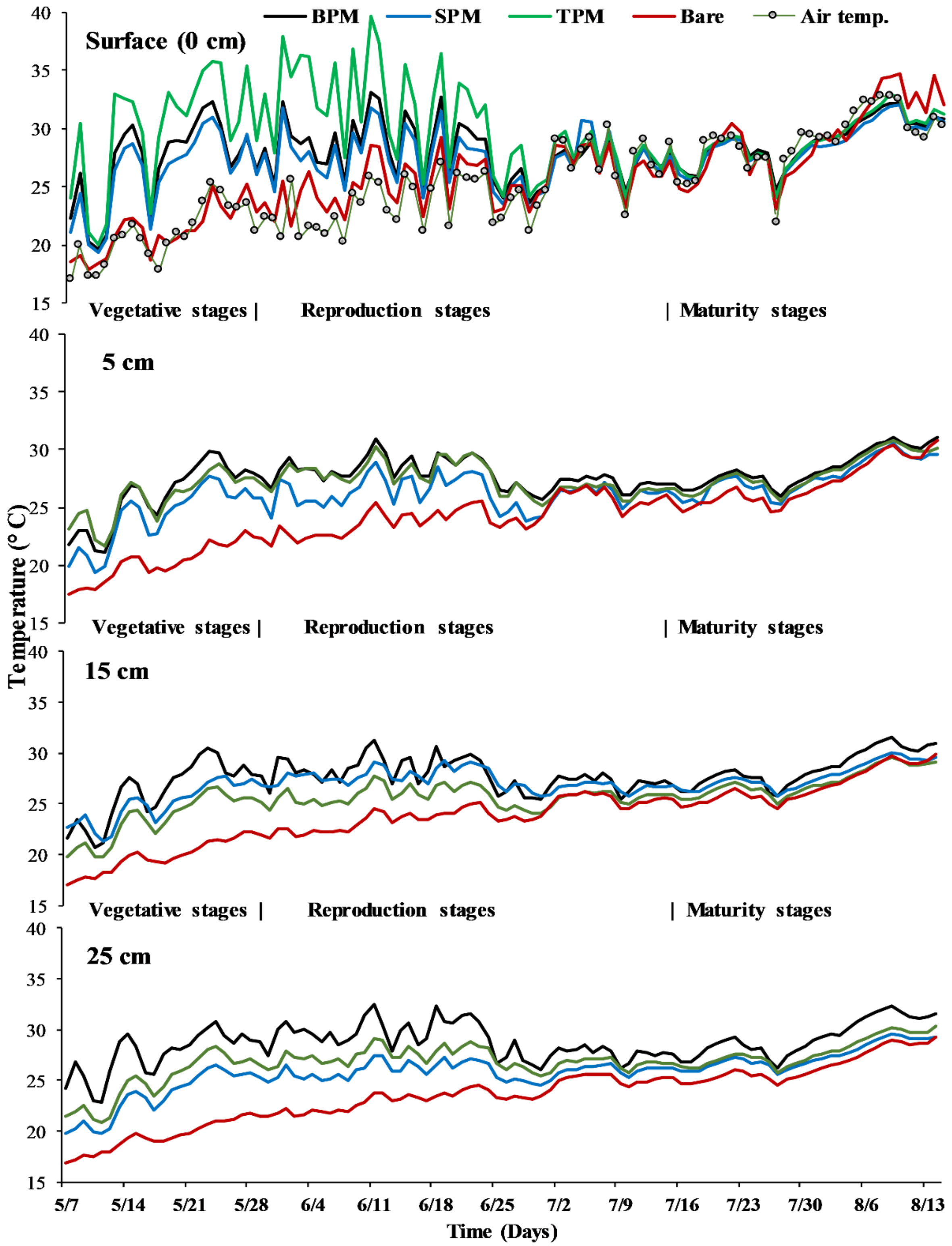

Figure 6.2 Mean daily soil temperature at 0 (soil surface), 5, 15 and 25 cm depths in the experimental soybean plots under three colored plastic film mulches and bare soil.

Table 6.1 Monthly mean soil temperature analysis of various treatments at 0–10, 10–20 and 20–30 cm depths of during the experimental period.

Soil depths (cm)	Treatments	Monthly soil temperature											
		May			**June**			**July**			**~ 14 August**		
		Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
5	BPM	33.4	22.9	25.6[a]	33.8	25.1	28.2[a]	29.0	25.3	27.2[a]	32.3	27.2	29.9[a]
	SPM	33.3	21.0	23.8[b]	34.5	20.7	27.9[b]	29.8	25.0	26.4[c]	32.6	25.9	29.1[c]
	TPM	31.1	24.4	25.9[a]	33.2	24.6	26.3[c]	28.7	24.8	26.7[b]	31.9	27.1	29.6[b]
	Bare	27.2	18.1	20.0[c]	29.3	18.7	23.7[d]	29.1	23.2	25.7[d]	34.4	25.3	29.0[c]
	SEm & CV (%)	0.11 & 12.4			0.08 & 7.8			0.04 & 4.1			0.08 & 5.0		
15	BPM	37.1	17.6	25.8[a]	37.1	22.9	28.2[a]	30.4	24.5	27.2[a]	33.7	26.6	30.1[a]
	SPM	28.7	17.9	23.2[c]	29.4	23	25.8[c]	27.6	24.1	26.0[c]	30.4	26.3	28.4[c]
	TPM	28.9	20.6	25.0[b]	30.4	25.5	27.7[b]	27.9	25.5	26.7[b]	30.5	27.2	29.0[b]
	Bare	24.3	14.8	19.6[d]	26.5	20.1	23.4[d]	27.3	23.4	25.5[d]	31.1	25.6	28.4[c]
	SEm & CV (%)	0.10 & 11.84			0.10 & 6.67			0.03 & 3.11			0.06 & 4.26		
25	BPM	35.7	20.4	27.6[a]	38.8	24.9	29.5[a]	30.9	25.3	27.8[a]	34.3	27.7	31.0[a]
	SPM	27.6	18.1	23.0[c]	28.4	24	26.0[c]	27.6	24.6	26.3[c]	30.2	26.8	28.6[c]
	TPM	29.5	19.8	24.5[b]	30.1	25.3	27.4[b]	28	25.4	26.8[b]	30.8	27.2	29.2[b]
	Bare	22.9	15.3	19.2[d]	25.3	20.6	23.1[d]	26.5	23.4	25.2[d]	29.9	25.7	27.9[d]
	SEm & CV (%)	0.09 & 10.83			0.06 & 6.29			0.03 & 2.81			0.06 & 3.90		

Means were calculated from daily hourly data of each month at different soil depths. The dissimilar lower-case letters within each column of the months indicate significant difference between the treatment means (P <0.05) by Tukey's HSD test. SEm: Standard Error means, and CV: Co-efficient of variance.

Soil temperature may be affected by color, thickness and characteristics of mulch material as well as by climatic location. Our study shows an increase in soil temperature under plastic mulching because of greater effects of radiation offered by the colored plastic films compared to bare soil. Increased soil temperature under transparent and black plastic mulching (5–8°C and 1–4°C, respectively) compared to bare soil was also reported by Melek and Atilla (2009). The reported performance of plastic mulching in increasing soil temperature is in the order: transparent > black > white (Liakatas et al., 1986) and black > blue > yellow > transparent (Al-Karaghouli et al., 1990). BPM is a light-impervious black body with good heat absorbing and radiating capacity and soil thermal conductivity is higher than that of air. Consequently, much of the energy absorbed by BPM can move to the soil through conduction when contact between the mulch and soil surface is good. TPM transmitted 85–95% of solar radiation with good light transmission capacity depending on thickness and degree of opacity of the plastic film (Li et al., 2018). Moreover, other possible factors (e.g. soil moisture content, film thickness, soil type and climate) may also influence heat flow into the soil profile. Therefore, our experimental result mainly shows that color of a plastic mulching can effectively alter soil temperature in the root zone of soybean crop.

6.3.3 Heat accumulation

Table 6.2 compares variation in accumulated heat under four mulching treatments at 5, 15 and 25 cm soil depths during the growing period of soybean. At all depths, plastic mulching augmented heat accumulation compared to bare soil. Film color of the mulches contributed positively in storing more heat, which might enhance the growth attributes of soybean. The amount of heat received and stored in the root zone was influenced by the film colors. BPM accumulated 1874 to 1762°D (degree day) at different soil layers of the root zone during the crop growing season, while the bare soil accumulated only 1430−1392°D. BPM accumulated 23% and 6% more heat in the root zone than the bare soil and TPM, respectively. The accumulated heat under different mulching treatments varied in the order: BPM > TPM > SPM > bare soil. The heat accumulation in terms of GDDs of soybean was the highest with BPM at 5, 15 and 25 cm depths. These observations exhibit the likelihood of early maturity of the crop with BPM compared to the other treatments.

Table 6.2 Soil heat accumulation measured at 5, 15 and 25 cm depths under three colored plastic film mulches and bare soil during the soybean cultivation period of 2016.

Soil depth	Soil heat accumulation (°D)			
(cm)	BPM	SPM	TPM	Bare
5	1760	1620	1730	1430
15	1770	1570	1700	1390
25	1870	1580	1690	1360

6.3.4 Soil moisture

Daily average soil moisture content at 5 cm depth varied with the rainfall events and presence of the plastic mulch; it was higher at the vegetative stage of soybean due to greater number of rainfall events and lower at the maturity stage (**Fig. 6.3**). Soil moisture content varied from 0.13 to 0.36 $cm^3\ cm^{-3}$ under the plastic mulch and 0.13 to 0.40 $cm^3\ cm^{-3}$ in bare soil during the growing period of the crop. The fluctuations of soil moisture content among the plastic mulching treatments were smaller compared to bare soil. The bare soil showed greater soil moisture content at 5 cm depth, with higher fluctuations due to direct infiltration of rainwater into soil surface (**Fig. 6.3**). The flat plastic film covered the soil surface and prevented rainwater from direct infiltration into the soil. But rainwater entered the soil surface through the planting holes and furrows outside of the plastic films and moved laterally below the soil surface. With BPM, soil water content was higher at the initial stage but decreased progressively with advancing growth stages. TPM provided higher soil water content at the maturity stage of soybean. The lower decreasing rates of soil moisture during each rainfall event under the plastic mulching treatments revealed smaller soil water consumption compared to bare soil.

6.3.5 Soil water consumption

Soil water consumption, *SWC*, is the soil moisture utilized by the crop under each treatment, where the water loss may include evaporation from soil surface, plant transpiration, and upward and downward water flow across the lower boundary of the effective root zone. *SWC* under each treatment was calculated at different growth stages of soybean by considering 14 major rainfall events, which primarily controlled *SWC* in different treatments. **Figure 6.4** demonstrates that plastic mulching

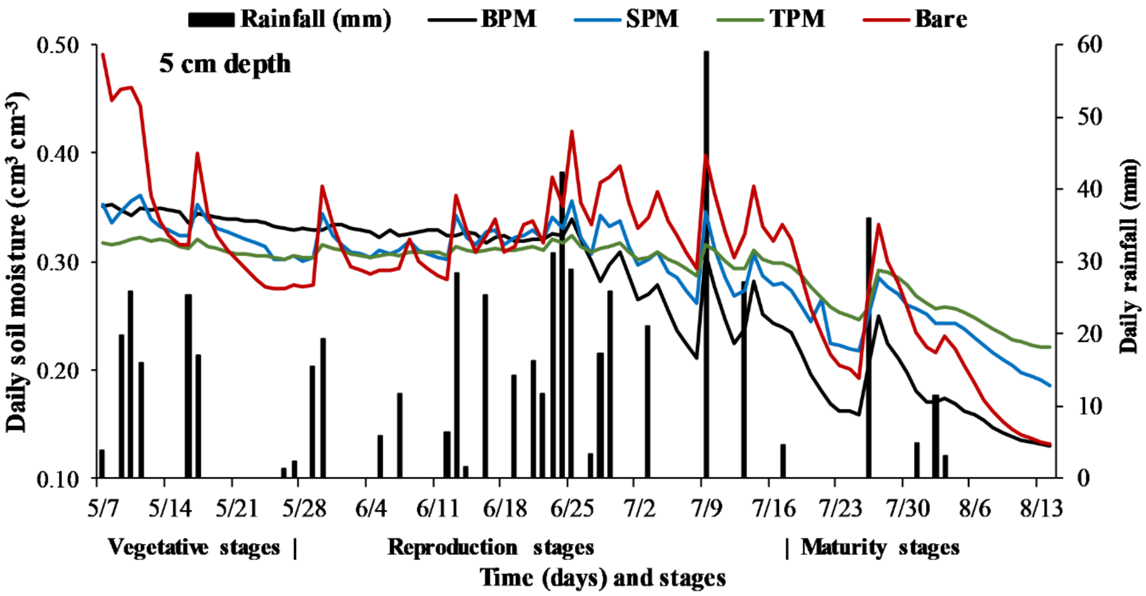

Figure 6.3 Variation of daily soil moisture content on rainfall events at 5 cm depth under three colored plastic film mulches and bare soil during the soybean cultivation period (April–August) of 2016.

significantly ($P < 0.05$) reduced *SWC* compared to bare soil at all growth stages of soybean. Bare soil always provided greater *SWC* between any two consecutive rainfall events. The cumulative *SWC* of bare soil was greater (142 mm) than that of the plastic mulching treatments, which provided *SWC* as: SPM (67 mm) > BPM (63 mm) > TPM (52 mm). Thus, the colored plastic films reduced *SWC* by 52–63% compared to bare soil. The trend of variation of *SWC*, observed under the three plastic mulching treatments during the growing season of soybean, was similar compared to bare soil. The *SWC* from 62 to 90 DAS of soybean growth was 1.2 mm d^{-1} under the bare soil; the BPM, SPM and TPM treatments consumed water at 1.0, 0.7 and 0.6 mm d^{-1}, respectively during this period. At the reproductive and maturity stages, accelerated physiological development of soybean plants occurred. Consequently, water uptake by the crop increased noticeably. The crop consumed less water during the vegetative stage under all treatments than in the reproductive and maturity stages (He et al., 2017). Similar to our results, previous studies also showed that soil evaporation was minimum under plastic mulching when compared with organic mulch and bare soil (Zribi et al., 2015). *SWC* was lowest for plastic mulching, followed by organic mulching and bare soil (Ghosh et al., 2006; Kader et al., 2017b). Reduced *SWC* under plastic mulching indicated conservation of soil moisture for longer period which could improve growth and yield of soybean.

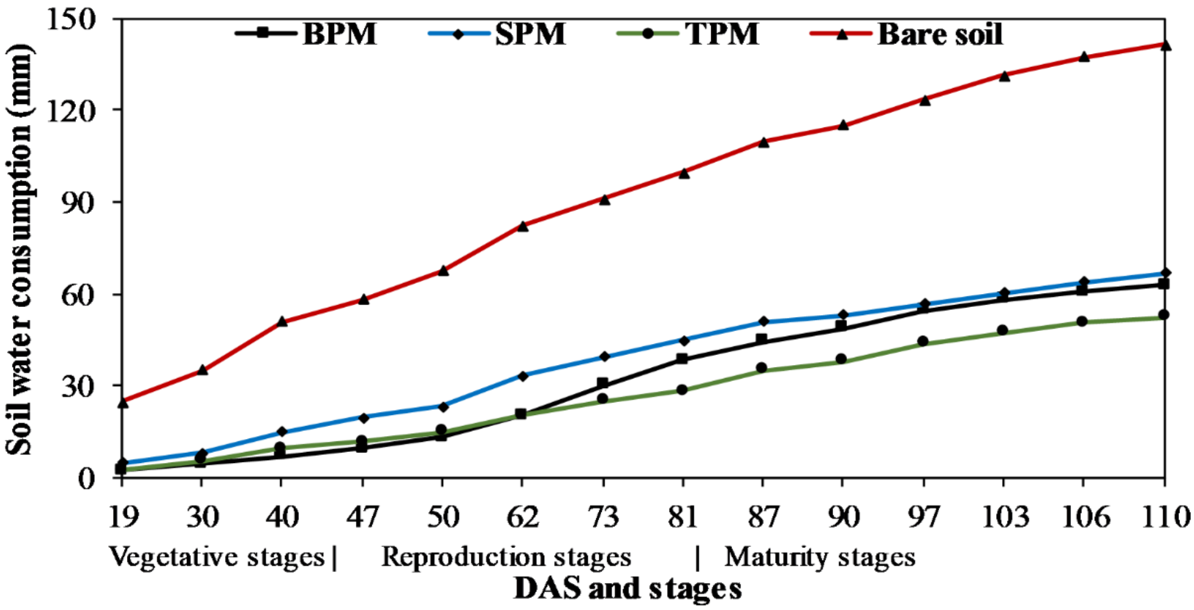

Figure 6.4 Cumulative soil water consumption in 0–30 cm soil profile under three colored plastic film mulches and bare soil during the soybean cultivation period (April–August) of 2016.

6.3.6 Soybean growth and yield

Colored plastic mulching strongly promoted the growth of soybean compared to bare soil, as evident in **Table 6.3**. The inferior soybean growth attributes under bare soil treatment might be due to soil water stress, low temperature and wet injury. BPM significantly (P < 0.05) improved total plant weight, and straw and grain yields of soybean (**Table 6.3**). **Table 6.4** compares the plant height and leaf chlorophyll content (expressed as SPAD value) of soybean at different growth stages under the four mulching treatments. The colored plastic mulch had significant effects on plant height that helped producing taller plants at 65, 85 and 108 days of soybean growth, while plant height was almost invariable for all treatments at 32 days due to leaf emergence (**Table 6.4**). Leaf chlorophyll content did not vary among the colored plastic mulching at different growth stages of soybean. BPM provided the highest leaf chlorophyll content at the reproductive stage (65, 85 DAS). At the time of harvesting (108 DAS), the effects of leaf chlorophyll diminished with drying up of the plant leaves. Improved leaf chlorophyll content under plastic mulching, compared to bare soil, might contribute for better growth attributes of soybean crop. Among the treatments, BPM provided the tallest plants at 65 DAS (**Table 6.4**).

Table 6.3 Analyzed parameters under various colored plastic films and bare soil used for soybean cultivation.

Analyzed components	BPM	SPM	TPM	Bare	Significance
Root length (cm)	23.4 ± 1.8	24.0 ± 1.5	18.4 ± 1.6	18.3 ± 1.5	NS
Root weight (g plant^{-1})	15.2 ± 1.6	13.4 ± 1.2	14.7 ± 1.6	10.4 ± 0.6	NS
Stem diameter (mm)	10.9 ± 0.8	10.8 ± 0.6	12.4 ± 0.6	9.8 ± 0.4	NS
Total weight (g plant^{-1})	475.2^{a} ± 50.7	412.9^{ab} ± 30.3	429.7^{ab} ±31.0	318.1^{b} ± 25.9	S
Nodulation (No. plant^{-1})	26.6 ± 2.5	20.7 ± 1.9	22.7 ± 2.1	19.0 ± 2.1	NS
Straw yield (g plant^{-1})	300.0^{a} ± 37.4	284.3^{ab} ± 26.7	264.6^{ab} ± 37.4	192.7^{b} ± 13.4	S
No. of grain per plant	39.8 ± 2.8	30.6 ± 2.5	37.1 ± 4.0	30.7 ± 3.0	NS
Grain yield (g plant^{-1})	190.5^{a} ± 37.4	113.7^{b} ± 10.4	146.0^{b} ± 11.4	115^{b} ± 12.7	S
No. of seed per plant	77.4 ± 5.0	55.4 ± 5.4	77.2 ± 6.4	60.5 ± 7.1	NS
Seed yield (g plant^{-1})	94.5^{a} ± 8.0	61.3^{b} ± 6.9	89.8^{ab} ± 8.6	71.2^{ab} ± 8.8	S
Total seed yield (g m^{-2})	277	174	270	206	-
SWC (mm)	63	67	52	142	-
Heat accumulation (°D)	5410	4770	5110	4180	-
$WP_{soybean}$ (g m^{-3})	4.4	2.6	5.2	1.5	-
HUE (g m^{-2} °D^{-1})	0.051	0.036	0.053	0.049	-

The values are shown as mean ± standard error; means were calculated from 10 randomly selected samples. The lower-case letters within each line indicate significant differences (P <0.05) by Tukey's HSD test. S: significantly different and NS: not significantly different.

Table 6.4 Plant height and leaf chlorophyll content at different growth stages of soybean cultivation under three colored plastic film mulches and bare soil treatments.

DAS	BPM	SPM	TPM	Bare	Significant
Plant height (cm)					
32	17.8 ± 0.5	18.6 ± 0.7	18.0 ± 0.9	18.2 ± 0.6	NS
65	67.2^{a} ± 2.1	63.2^{ab} ± 1.7	65.6^{b} ± 2.1	55.0^{c} ± 1.6	S
85	69.0^{a} ± 2.1	70.4^{a} ± 1.2	71.6^{a} ± 1.3	63.0^{b} ± 2.5	S
108	68.0^{b} ± 1.4	77.2^{a} ± 2.0	71.0^{ab} ± 1.0	67.4^{b} ± 2.3	S
Leaf chlorophyll content (SPAD value)					
32	41.0^{b} ± 1.3	42.1^{ab} ± 0.5	41.9^{ab} ± 1.2	43.2^{a} ± 1.1	S
65	46.0^{a} ± 1.3	41.8^{b} ± 1.5	45.1^{a} ± 0.9	40.0^{b} ± 1.2	S
85	52.6^{a} ± 1.0	51.2^{ab} ± 0.6	50.3^{ab} ± 0.8	48.6^{b} ± 1.1	S
108	37.8^{b} ± 1.5	37.9^{b} ± 0.7	42.5^{a} ± 1.6	38.4^{b} ± 1.7	S

The values are shown as mean ± standard error; means were calculated from 7 samples. Means with the same letter in a row do not differ significantly at 5% probability level analyzed by Tukey's test. DAS: Day after sowing, S: significantly different and NS: not significantly different.

The highest accumulated soil temperature under BPM might reduce the crop growing period by early occurrence of physiological stages of soybean plant compared to other treatments (Subrahmaniyan et al., 2011). The increasing trend of soil temperature, due to the color of the plastic film, advanced crop growth and reproductive processes, which significantly enhanced production of rainfed soybean (**Fig. 6.2**, **Table 6.3**). Black plastic film mulch provided better growth attributes of stem diameter, root length and weight, nodulation, number of grains and seeds per plant, and yield of soybean than the other colored plastic mulches; bare soil produced the poorest plant attributes (**Table 6.3**). BPM and TPM, augmented soybean yield by 31–34% compared to bare soil. Increased soybean yield under mulching was also reported by several investigators. For example, rainfed soybean cultivation in India with mulching increased yield 16% compared to bare soil (Dass and Bhattacharyya, 2017), and Sekhon et al. (2005) reported the finding of 4.4–68.3% increase in soybean yield under mulch treatment. Water productivity, *WP*, associated with yield and cumulative soil water consumption, *SWC*, was the highest (5.2 g m^{-3}) under TPM due to the lowest *SWC* (52 mm). The bare soil provided the lowest *WP* of soybean (1.5 g m^{-3}) due to the highest *SWC* (142 mm). The order of *WP* obtained under the mulching treatments was: TPM > BPM > SPM > bare soil. The highest *WP* under TPM was also reported by Subrahmaniyan et al. (2018). Heat use efficiency (*HUE*), defined as the ratio of yield of soybean to cumulative soil heat in the root zone, was the highest under TPM, followed by BPM (**Table 6.3**). The higher cumulative heat in the 0–30 cm rooting depth augmented the yield per square meter in BPM and TPM, while SPM and bare soil reduced the yield due to lower cumulative heat (**Fig. 6.5**).

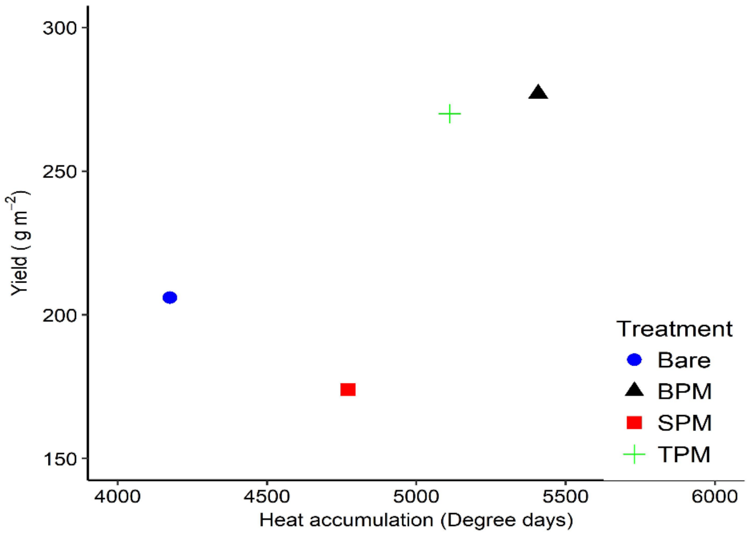

Figure 6.5 Variation of the yield of rainfed soybean cultivated under black, silver and transparent plastic mulching and bare soil treatments with cumulative heat accumulation.

Our results suggested that BPM provided the highest yield (277 g m^{-2}) due to increased heat accumulation (5410°D) in the 0–30 cm root zone that also provided higher growth attributes of rainfed soybean (**Fig. 6.5**, **Table 6.3**). Therefore, the observed results clearly indicate that BPM and TPM helped increase temperature at various soil depths compared to bare soil and ultimately improved soybean yield in central Japan area. However, from economic viewpoint, the difference between the cost of plastic films and increased revenue becomes important and changeable with the economic and social conditions of each country and crop year. It can be concluded that the colored plastic mulching raised soil temperature, reduced *SWC* and improved leaf chlorophyll content; all these factors enhanced growth attributes and augmented yield of rainfed soybean in our experiment.

6.4 Conclusions

This study concluded that color of plastic film greatly influenced soil surface temperature. Bare soil provided stronger relationship (R^2 = 0.85) between soil surface temperature and air temperature than the plastic mulching (SPM, BPM and TPM) treatments, which provided much weaker relationships (R^2 = 0.47, 0.33 and 0.03, respectively) between these two temperature sets. Black, silver and transparent plastic film mulches, compared to bare soil, raised soil temperature by 3–7°C at 5, 15 and 25 cm soil depths at early growth stages of rainfed soybean; at later growth stages, the increase in temperature was only 1–2°C. The three plastic mulches conserved soil moisture and lowered *SWC* by 52–63% compared to bare soil. These mulches provided a favorable crop growing environment, which improved soybean yield by 31–34% compared to bare soil in central Japan. Plastic mulching increased cumulative heat accumulation compared to bare soil in 0–30 cm root zone, while BPM stored a higher quantity of heat than TPM. Moreover, BPM provided the highest seed yield of soybean by maintaining high soil temperature, reducing *SWC* and improving growth attributes like plant height, root length, stem diameter, and nodulation. Although black, silver and transparent colored plastic films are applicable for soil mulching materials in central Japan areas to boost up soil temperature and conserve soil moisture for enhancing growth and yield of summer vegetable crops, the black colored plastic film mulching is explicitly recommended for its better performance.

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CHAPTER 7

Numerical simulation of hydrothermal regimes of straw mulched soil

7.1 Introduction

Straw mulching is an important water-saving technology in arid and semi-arid regions. It can alter the micro-ecological environment of a soil by restricting evaporation and controlling water and heat flows (Kader et al., 2017a). The straw can reduce soil evaporation by minimizing the exchange of water vapor between the soil and atmosphere (Huang et al., 2005). Moreover, the thermal properties of mulched-soils affect soil temperature variably (Pramanik et al., 2015) due to heat exchange among air, mulch layer and soil. Therefore, water and heat transport through the soil profile under different mulching types is greatly controlled by the characteristics of surface covers, soil properties and climatic environment. In order to quantify the effects of straw mulching on plant growth system, numerical simulation of the effects of mulching might be effective for understanding the behaviors of water and heat flow in field soils. Numerical simulations for predicting soil water and heat flow regimes beneath mulched soils are important to increase the opportunity for efficient use of mulching in agriculture.

Numerical simulations of mulched soils are, however, complicated due to interactions of the mulch and soil surface, and difficulty in correct consideration of boundary layers and accurate estimations of soil evaporation (Li et al., 2015; Šimůnek et al., 2016). Although numerical simulations of mulching and different soil conservation practices with HYDRUS-1D (Šimůnek et al., 1998) have been reported by several investigators (Dahiya et al., 2007; Zhao et al., 2010; Kodešová et al., 2014; Gonzalez et al., 2015; Liang et al., 2017), none of them modeled straw mulching. Previous studies that quantified the effects of plastic mulching with HYDRUS software can be categorized into: changing of boundary conditions (Chen et al., 2018; Saglam et al., 2017), reducing of crop coefficient (Li et al., 2015), separating of potential evaporation and transpiration (Chen et al., 2014; Zhang et al., 2018), reducing of rainfall by a fraction (Zhao et al., 2018) and modifying of energy balance (Liang et al., 2017). These simulation studies were limited to plastic mulch only, and most of them were unable to predict the vapor and heat flows. Kodešová et al. (2014) simulated water and heat flows using HYDRUS-1D under grass, concrete and bark covers, but they neglected vapor diffusion and crop water uptake. Organic mulching influences the coupling of soil water, vapor and heat flow processes, which may depend on the characteristics of mulch materials like thickness, roughness, organic matter content and pore space (Kader et al., 2017a; Akhtar et al., 2019). So, a numerical model may help regulating the effective management of soil water and thermal regimes under mulching practices.

In this chapter, water retention functions of straw material were introduced by a novel approach into a numerical model (HYDRUS-1D) to show the effects of mulching on soil hydrothermal properties. An extra layer of straw was incorporated on the soil surface to simulate the coupled flow of vapor, water and heat through the mulched soil. The aim was to simulate water and heat flow regimes under rice straw mulching and bare soil in order to analyze water consumption, ratio of vapor to total water transport, water balance and heat storage from the root zone in the field soil during two years of rainfed soybean cultivation in central Japan.

7.2 Materials and methods

7.2.1 Field experiments

Soybean was grown under two soil cover treatments in the experiments: rice straw mulching and bare soil in the year of 2015 and 2016. The thickness of straw on soil surface was approximately 3 cm.

7.2.2 Data monitoring

Net radiation was estimated using climatic data measured at study site following Chang (1970) as:

$$R_n = (1-r)R - \sigma T^4 \left(286.18 + 202.60\, {}^{R}\!/_{R_a} - 45.24\sqrt{e_d} - 10.92\, {}^{R}\!/_{R_a\sqrt{e_d}}\right) \quad (7.1)$$

where R_n is net radiation (MJ m^{-2} d^{-1}), r is reflection coefficient (albedo) set as 0.23, T is air temperature (K), R is solar radiation (MJ m^{-2} d^{-1}), R_a is extra-terrestrial solar radiation (MJ m^{-2} d^{-1}), σ is Stefan–Boltzmann constant (4.90 ×10^{-9} MJ m^{-2} K^{-4} d^{-1}) and e_d is saturation vapor pressure (hPa). Reference crop evapotranspiration (ET_o) was calculated by using Penman-Monteith method (Allen et al., 1998). The temporal variations of daily rainfall and ET_o over the crop growing period of 2015 and 2016 are illustrated in **Fig. 7.1** that were used as input data to define boundary in the simulations by HYDRUS-1D model.

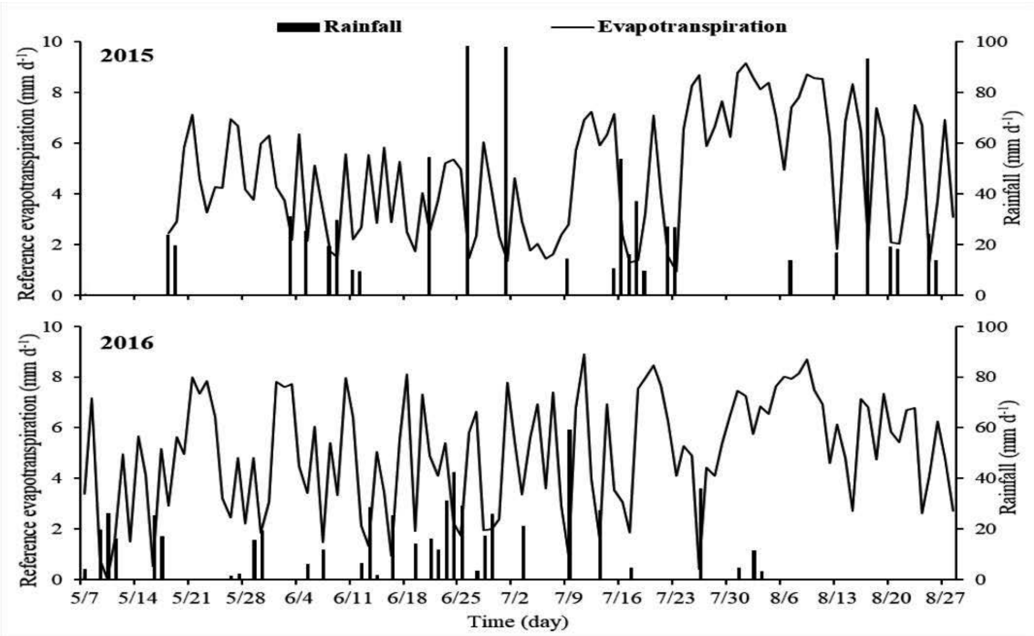

Figure 7.1 Daily reference evapotranspiration (ET_o) and rainfall in the experimental area during soybean growing seasons of 2015 and 2016.

7.2.3 Numerical simulations

7.2.3.1 Soil water flow with vapor transport

The HYDRUS-1D software version 4.16.0110 (Šimůnek et al., 2013) was used to simulate soil water and heat transports. Water vapor and evaporation from the straw layers were taken into account in analyzing the effects of straw mulching on water flow through the soil profile. Thermal properties between the mulch layer and soil surface often change depending on soil moisture condition, which is influenced by vapor transport. The liquid water and vapor transport with root uptake functions can be expressed by (Richards, 1931; Saito et al., 2006):

$$\frac{\partial \theta_T(h)}{\partial t} = \frac{\partial}{\partial z}\left[(K + K_{vh})\left(\frac{\partial h}{\partial z} + 1\right) + (K_{LT} + K_{vT})\frac{\partial T}{\partial z}\right] - S \qquad (7.2)$$

where h is pressure head (cm), T is temperature (K), θ_T is total volumetric water content or θ_T = [θ (volumetric soil water content) + θ_v (vapor content)] (cm^3 cm^{-3}), K and K_{LT} are isothermal and thermal hydraulic conductivity (cm d^{-1}), respectively of the liquid phase, K_{vh} and K_{vT} are isothermal and thermal vapor hydraulic conductivity (cm d^{-1}), respectively, t is time (d), z is upward spatial coordinate (cm) and S is a sink term, referring to root water uptake (d^{-1}). The unsaturated soil hydraulic properties were modeled for the entire flow domain by applying van Genuchten-Mualem model (van Genuchten, 1980) expressed as:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} \qquad (7.3)$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad (7.4)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (7.5)$$

where θ_s is saturated soil moisture content (cm^3 cm^{-3}), θ_r is residual soil moisture content (cm^3 cm^{-3}), K_s is saturated hydraulic conductivity (cm d^{-1}), α (cm^{-1}) and n (-) are shape parameters of water retention curve, S_e is effective saturation (-), and l (-) is pore connectivity parameter that is assumed to be 0.50 for all cases (Mualem, 1976). The isothermal vapor hydraulic conductivity, K_{vh}, and thermal vapor hydraulic conductivity, K_{vT}, are described (e.g. Nassar and Horton, 1989; Saito et al., 2006) as:

$$K_{vh} = \frac{D_v}{\rho_w}\rho_{vs}\frac{Mg}{R_u T}H_r \qquad (7.6)$$

$$K_{vT} = \frac{D_v}{\rho_w}\eta_e H_r \frac{d\rho_{vs}}{dT} \qquad (7.7)$$

where D_v is vapor diffusivity in soil (cm^2 s^{-1}), ρ_w is density of liquid water (kg cm^{-3}), ρ_{vs} is saturated vapor density (kg cm^{-3}), M is molecular weight of water (kg mol^{-1} = 0.018015 kg mol^{-1}), g is gravitational acceleration (9.81 m s^{-2}), R_u is universal gas constant (J mol^{-1}K^{-1} = 8.314 J mol^{-1}K^{-1}), η_e is enhancement factor (-) (Cass et al., 1984) and H_r is relative humidity (-).

7.2.3.2 Root uptake functions

The sink term (S) expresses the volume of water removed per unit time from a unit volume of soil due to plant water uptake and is computed according to Feddes model (Feddes et al., 1978) expressed as:

$$S(h, z) = \alpha(h) b(\, z) T_p \qquad (7.8)$$

where $\alpha(h)$ is water stress response function (-) due to root water uptake as a function of soil water pressure head, $b(z)$ is normalized water uptake distribution function (cm^{-2}) and T_p is potential transpiration rate (cm d^{-1}). The root water uptake parameters were explained based on Feddes' model for bean (soybean crop) from HYDRUS internal database (**Table 7.1**). The growth data of soybean, plant height and root depth, were selected from field measurements. The seasonal leaf extinction coefficient of soybean was taken as 0.49 following Adeboye et al. (2017).

Table 7.1 Root water uptake parameters used in HYDRUS-1D simulations.

Crop	Root water uptake parameters						
	h_0	h_{Opt}	h_{2H}	h_{2L}	h_3	r_{2H}	r_{2L}
	(cm)					(cm d^{-1})	
Soybean	–15	–30	–750	–2000	–8000	0.5	0.1

Note: h_0: Pressure head below which roots start to extract water from the soil; h_{Opt}: Pressure head at which maximum water uptake exists; h_{2H}: Limiting pressure head below which roots can no longer extract water at the maximum rate; h_{2L}: Pressure head having same meaning of h_{2H} but for a potential transpiration rate of r_{2L}; h_3: Pressure head below which root water uptake ceases; r_{2H} and r_{2L}: High and low potential transpiration rates for an optimal range of pressure heads.

7.2.3.3 Soil water consumption

Soil water consumption (*SWC*), estimated based on equation **4.1** (**section 4.2.1**). In addition, six major consecutive rainfall events were selected to calculate *SWC* for the observed and simulated soil moisture contents of each treatment. The d_i (depth of soil layer) was 10 cm for each observation layer corresponding to the measurement depths of 5, 15 and 25 cm; however, d_i was 1 cm for the simulations since the node interval was set at 1 cm. The number of soil layers was 3 for observation period and 30 for simulation period. Therefore, simulated *SWC* was estimated from the soil moisture reduction of top 30 nodes within 0–30 cm profile. In addition, *SWC* of hypothetical straw layer was calculated from the top 0–3 cm layer of simulated straw treatment for both crop years. Furthermore, the daily water consumption was estimated for the observed and simulated data of each treatment.

7.2.3.4 Soil heat flow

The governing equation for sensible and latent heat transport with water vapor flow and heat sink by root water uptake utilized in HYDRUS-1D was given by (Saito et al., 2006):

$$C_p(\theta)\frac{\partial T}{\partial t} + L_0\frac{\partial \theta_v}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(\theta)\frac{\partial T}{\partial x}\right) - C_w q\frac{\partial T}{\partial x} - C_v\frac{\partial q_v T}{\partial x} - L_0\frac{\partial q_v}{\partial x} - C_w ST \qquad (7.9)$$

where L_0 is volumetric latent heat of vaporization (J m^{-3}); q is water flux (cm d^{-1}); q_v is flux density of water vapor (cm d^{-1}); $\lambda(\theta)$ is apparent thermal conductivity of soil (W m^{-1} K^{-1}); and C_p, C_w and C_v are volumetric heat capacities of moist soil, liquid water and water vapor (J m^{-3} K^{-1}), respectively. The thermal conductivity as a function of soil moisture content is expressed by (Chung and Horton, 1987):

$$\lambda(\theta) = b_1 + b_2\theta + b_3\theta^{0.5} \qquad (7.10)$$

where b_1, b_2 and b_3 are empirical parameters (W m^{-1} K^{-1}). In equation (**7.10**), the volumetric heat transport parameters were explained by de Vries (1963) and further modified by Šimůnek and van Genuchten (2008) as:

$$C_p(\theta) = C_n\theta_n + C_o\theta_o + C_w\theta \qquad (7.11)$$

where subscripts *n*, *o*, *w* represent solid phase, organic matter and liquid phase in a soil, respectively. The volume fraction of solid phase, θ_n (cm^3 cm^{-3}), was determined by:

$$\theta_n = 1 - \theta_s - \theta_o \qquad (7.12)$$

where θ_o is volume fraction of soil organic matter (cm^3 cm^{-3}).

7.2.4 Model parameterizations

7.2.4.1 Initial and boundary conditions

The initial and boundary conditions used in HYDRUS-1D model for simulating soil water and heat flow under straw mulching are illustrated in **Fig. 7.2**. **Figure 7.2** also depicts the schematic view of sensors, soil surface and straw mulch layers incorporated in the soybean plots. The conditions, set up for each boundary and input parameters, are described in **Table 7.2**. The input data for straw mulching and bare soil treatments were daily rainfall, net radiation and air temperature during the experimental period of 2015 and 2016. The mulching and bare soil treatments were discriminated by considering an additional 3 cm layer of straw materials on the soil surface (**Fig. 7.2**). A variable upper temperature

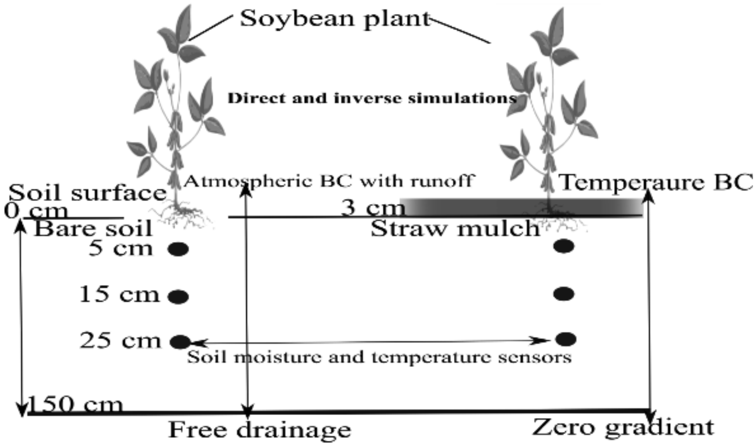

Figure 7.2 Conceptual diagram of HYDRUS-1D simulations incorporated with straw layers and sensors' positions.

Table 7.2 Boundary Conditions (BC) and input data for HYDRUS-1D modeling.

Parameters	Boundary	Conditions set-up	Input data
Water flow	Upper	Atmospheric BC with surface runoff	Rainfall, air temperature, humidity
	Lower	Free drainage	-
Heat flow	Upper	Temperature BC	Net radiation, wind speed, sunshine hours
	Lower	Zero gradient	-

boundary condition was adopted using air temperature, measured at 2 cm height of each treatment and year. The simulated profiles of the bare and mulched soils were 150 and 153 cm, respectively with corresponding node number of 151 and 154 since free drainage was considered at the bottom. The soil profile of the bare treatment was sectioned into three layers (0–10, 10–20 and 20–150 cm) and that of straw treatment was sectioned into four layers: 0–3 cm straw layer and three soil layers (3–13, 13–23 and 23–153 cm). The initial conditions were set in terms of field measured soil moisture and temperature at 5, 15 and 25 cm depths at the beginning of simulation period for both crop years. Temperature dependence of soil hydraulic parameters was included in the study by considering temperature dependence of viscosity of water and surface tension between water and air.

7.2.4.2 Parameters optimization

Numerical simulations of soil water and heat flow under the two treatments were done for the periods from 12 June to 27 August (77 days) in 2015 and from 5 May to 14 August (101 days) in 2016. The data sets of 2015 and 2016 were used to validate the model. First, soil hydraulic parameters (θ_r, θ_s, α, and n) were estimated from the laboratory-measured retention data by using RETC software package (van Genuchten et al., 1991). The estimated parameters were used as the initial values for inverse solution in estimating the optimal soil hydraulic parameters. It is noted that the values of the parameters obtained in laboratory test cannot be used as the fixed values since the soil was heterogeneous rather

Table 7.3 Measured soil hydraulic parameters and HYDRUS-1D optimized hydraulic parameters under straw and soil layers in different treatments.

Treatments	Depth (cm)	θ_r (cm^3 cm^{-3})	θ_s	α (cm^{-1})	n (-)	K_s (cm d^{-1})
Straw layer	0–3	0.003	0.66	0.498	1.316	475.2
Laboratory measurement	5	0.09	0.54	0.044	1.291	218.0
	15	0.09	0.46	0.015	1.268	197.5
	25	0.09	0.43	0.014	1.201	160.0
Bare (2015)	5	0.09	0.54	0.071	1.291	218.0
	15	0.09	0.46	0.039	1.268	197.5
	25	0.09	0.43	0.032	1.241	160.0
Straw (2015)	5	0.09	0.54	0.044	1.291	218.0
	15	0.09	0.46	0.015	1.246	197.5
	25	0.09	0.43	0.014	1.256	160.0
Bare (2016)	5	0.09	0.53	0.038	1.252	218.0
	15	0.09	0.48	0.014	1.284	197.5
	25	0.09	0.47	0.020	1.289	160.0
Straw (2016)	5	0.09	0.54	0.044	1.291	218.0
	15	0.09	0.49	0.015	1.246	197.5
	25	0.09	0.43	0.032	1.205	160.0

Note: The hydraulic parameters of straw layer were optimized by inverse solutions. The optimized values of θ_s, α and n in different treatments are small compared to laboratory measured values.

than homogeneous over the whole year and the hydraulic parameters might have changed. Water flow through the bare soil was simulated using optimized van Genuchten parameters derived from laboratory-measured data and, afterward, α and n (equation **7.3**) were further optimized simultaneously by inversion procedure (**Table 7.3**). Secondly, the optimized soil hydraulic parameters of the bare soil for 2015 were fixed and used for validation of the results in bare soil for 2016. A 3-cm thick layer of straw mulch above the soil surface of straw mulched treatment was considered that resembled a four-layer calculation domain profile with this treatment. Usually, the straw surface acted like a coarse soil. So, greater θ_s and K_s were chosen as their initial values for optimization since the straw layer had greater porosity and hydraulic conductivity compared to soil. In case of the mulching treatment, final optimization of the parameters (θ_r, θ_s, α, n and K_s) of hydraulic function for the straw layer was conducted by inverse simulation, where the soil hydraulic parameters were fixed by bare soil simulation. The optimized hydraulic parameters of the straw layer for 2015 were then used for 2016. Moreover, θ_r and K_s of the soil layers were kept fixed for both treatments and years (**Table 7.3**). Further optimizations of θ_s, α and n of the soil layers, depending on the treatment and year, were done by trial-error procedure to obtain the best-fitting soil moisture content (**Table 7.3**). The combine water and heat flow simulations were run for 2015 and 2016, where water flow parameters were kept fixed, and heat flow parameters were estimated by inverse solutions using Levenberg–Marquardt non-linear minimization method

Table 7.4 Soil thermal parameters (θ_n: volumetric fraction of solid phase; θ_o: volumetric fraction of organic matter; D: dispersivity; b_1, b_2 and b_3: empirical parameters of thermal conductivity; C_n, C_o and C_w: volumetric heat capacity of solid, organic matter and liquid water phase, respectively used for heat flow simulations in HYDRUS-1D modeling.

Layers	Depth (cm)	θ_n	θ_o	D	b_1	b_2	b_3	C_n	C_o	C_w
		(cm^3 cm^{-3})		(cm)	(W m^{-1} K^{-1})			(MJ m^{-3} K^{-1})		
Straw	0–3	0.20	0.120	5.0	0.11	0.28	1.10	0.82	1.83	4.18
1st soil	0–10	0.418 ± 0.00	0.037	3.05 ± 0.45	0.24	0.39	1.53	1.80 ± 0.50	2.30 ± 0.77	4.18
2nd soil	10–20	0.506 ± 0.02	0.031	5.74 ± 1.66	0.24	0.39	1.53	3.88 ± 0.91	2.10 ± 0.80	4.18
3rd soil	20–30	0.542 ± 0.00	0.023	3.30 ± 0.42	0.24	0.39	1.53	5.48 ± 0.00	2.57 ± 0.70	4.18

Note: Values (mean ± standard error) of θ_n, D, C_n and C_o for soils were optimized by inverse solution.

(Šimůnek et al., 1998). In our model, the thermal conductivity parameters of each soil layer were fixed at $b_1 = 0.24$, $b_2 = 0.39$ and $b_3 = 1.53$ for loamy soil as suggested by Chung and Horton (1987). Moreover, the thermal conductivity of straw material is lower compared to soil (van Donk and Tollner, 2000), and lower values of b_1, b_2 and b_3 for organic materials (bark and pine) were reported by Kodesová et al. (2013). Therefore, lower values of b_1, b_2 and b_3 of straw layer were set at initial simulations and thereby optimized by inversion procedure (**Table 7.4**). Consequently, θ_n was very small compared to soil layers for calculating $C_p(\theta)$ of straw layer. This was due to greater porosity of dry straw and organic matter of straw materials was high, assumed to be 12% (**Table 7.4**). Although Kodesová et al. (2013) found smaller $C_p(\theta)$ for organic mulching, the three soil layers under investigation revealed greater volumetric heat capacity than straw layers. It is noted that C_w was fixed for both soil and straw layers (**Table 7.4**). The inverse optimization provided lower C_n and C_o of straw, but the soil layers provided greater C_n and C_o; the overall value of $C_p(\theta)$ however remained similar to that for loamy soil (**Table 7.4**). The dispersivity (D) of each soil layer was optimized by inverse simulations between 3 cm and 10 cm, while it was kept fixed as 5 cm for straw layer (**Table 7.4**). The four heat transport parameters (θ_n, D, C_n and C_o), optimized by inverse simulations for 2015, were used as fixed values in simulations for 2016 for each treatment.

7.2.5 Statistical performance of HYDRUS-1D model

The statistical indicator, coefficient of determination (R^2), was used to reflect the degree of correlation between the simulated and observed values of soil moisture and soil temperature for each treatment. The performance of the model was evaluated by Root Mean Square Error ($RMSE$) as expressed by:

$$RMSE = \left[\frac{1}{N}\sum_i (P_i - O_i)^2\right]^{1/2} \quad (7.13)$$

where N is number of observations and P_i and O_i are simulated and measured values of the parameters, respectively.

7.3 Results

7.3.1 Hydraulic functions of soil and straw mulch

Figure 7.3 shows the water retention curves from the laboratory-measured data and optimized water retention curves for 5, 15 and 25 cm soil layers and straw layer. The residual water content (θ_r) did not significantly vary between the two treatments and years of experiment (**Table 7.3**). The values of θ_r that depends largely on soil texture did not vary among the treatments and, consequently, did not influence simulation of soil moisture (Šimůnek et al., 1998; Ramos et al., 2017). To obtain the best fitted soil moisture content, α and n (equation **7.3**) at 0–10, 10–20 and 20–30 cm profiles were optimized by trial-error procedure (**Table 7.3**). The soil hydraulic functions of the two years' field experiments were different due to disturbance in the soils by tillage operations, although the optimized soil hydraulic parameters were kept within similar trend for the two treatments and periods of experiment (**Fig. 7.3**). The hydraulic characteristics of 3-cm straw layer above the soil surface were considered having greater θ_s (saturated water content) and K_s; the straw layer shows different patterns from the soil layers (**Fig. 7.3** and **Table 7.3**).

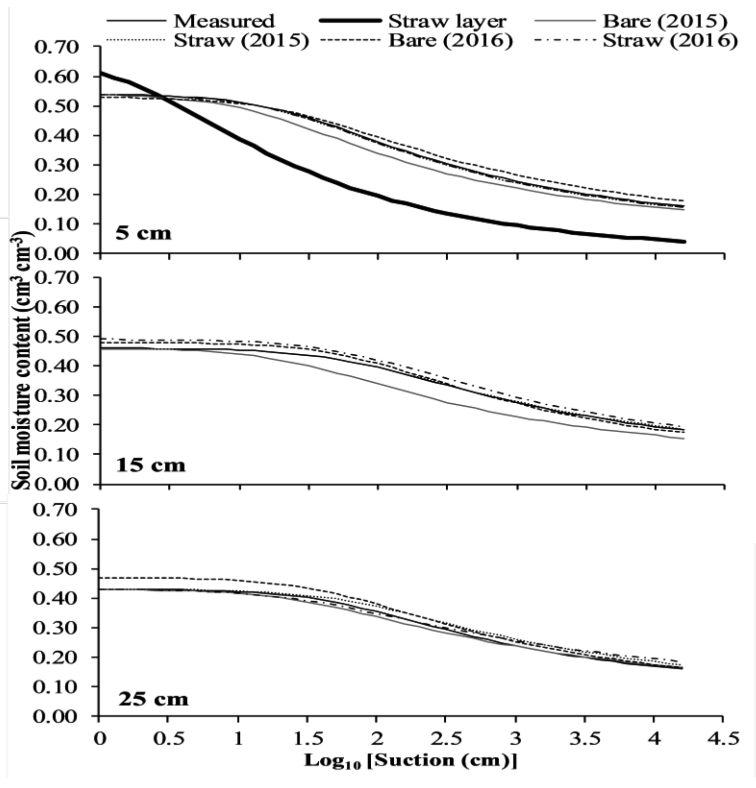

Figure 7.3 Optimized water retention curve with deviation from the laboratory-measured data at three soil layers and one straw layer for two treatments of 2015 and 2016 crop period used in HYDRUS-1D simulations.

7.3.2 Soil moisture dynamics

Soil water content increased with rainfall events and decreased gradually until the next rainfall event due to the combined effect of infiltration, evaporation and plant water uptake. **Figures 7.4** (A, B) and **7.5** (A, B) illustrate the measured and simulated volumetric soil water contents of the bare soil and straw treatment at 5, 15 and 25 cm soil depths during the soybean growing periods of 2015 and 2016, respectively. The estimated water content patterns of straw layers over the crop period are illustrated in **Figs. 7.4** (B) and **7.5** (B). A good relationship is obtained between the measured and simulated soil moisture contents at 5, 15 and 25 cm depths of the bare soil and straw-mulched soil. The HYDRUS-1D model fairly approximated the observed data as demonstrated by large values of R^2 and small values of *RMSE* (**Table 7.5**). R^2 varied from 0.64 to 0.92 for the bare soil and 0.63 to 0.83 for straw-mulched soil. *RMSE* varied from 0.018 to 0.038 $cm^3\ cm^{-3}$ in 2015 and 0.030 to 0.044 $cm^3\ cm^{-3}$ in 2015 for the bare soil. The corresponding *RMSE* for the straw-mulched soil was 0.027 to 0.037 $cm^3\ cm^{-3}$ in 2015 and 0.016 to 0.036 $cm^3\ cm^{-3}$ in 2016. Therefore, the model reliably simulated soil moisture content at 5, 15 and 25 cm depths under straw-mulched and bare soil treatments.

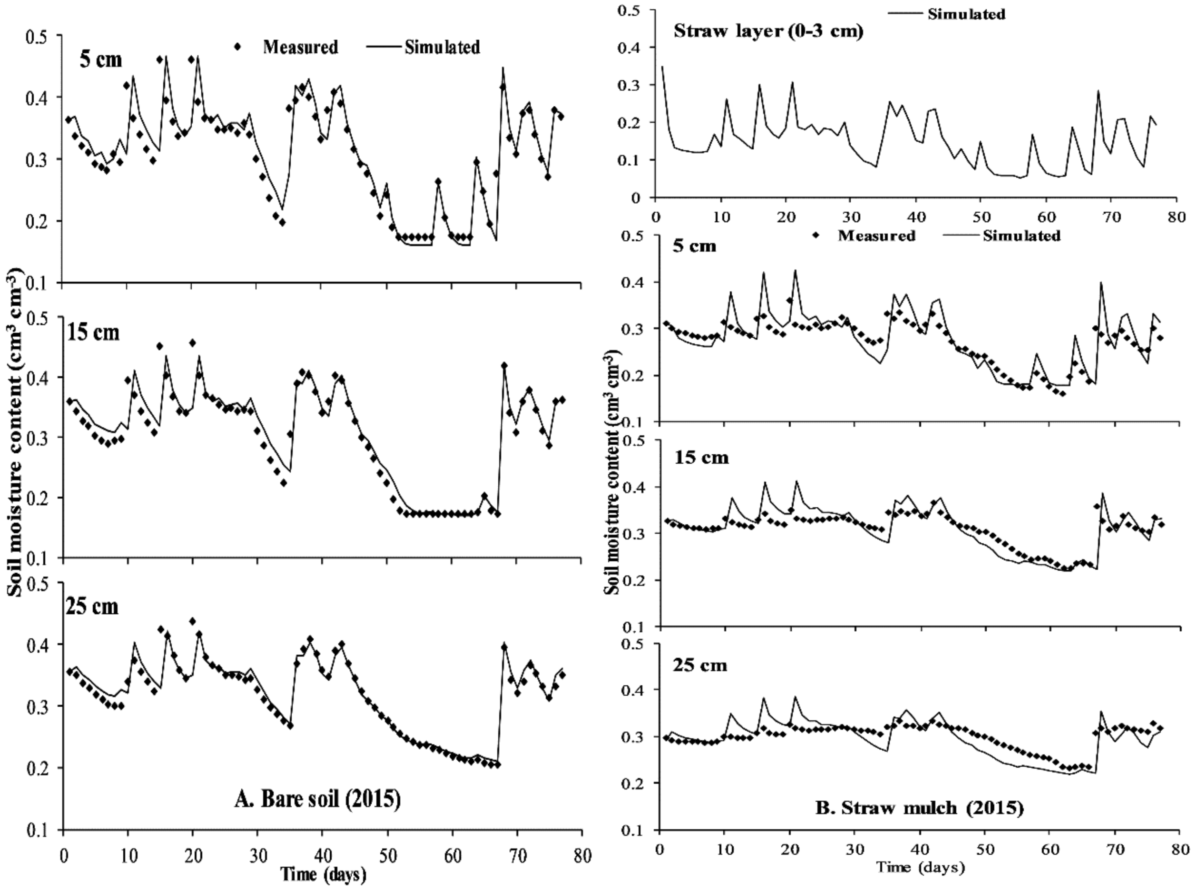

Figure 7.4 Simulated and measured soil moisture contents at 5, 15 and 25 cm depths under (A) bare soil and (B) straw mulch treatments during the soybean growing season of 2015.

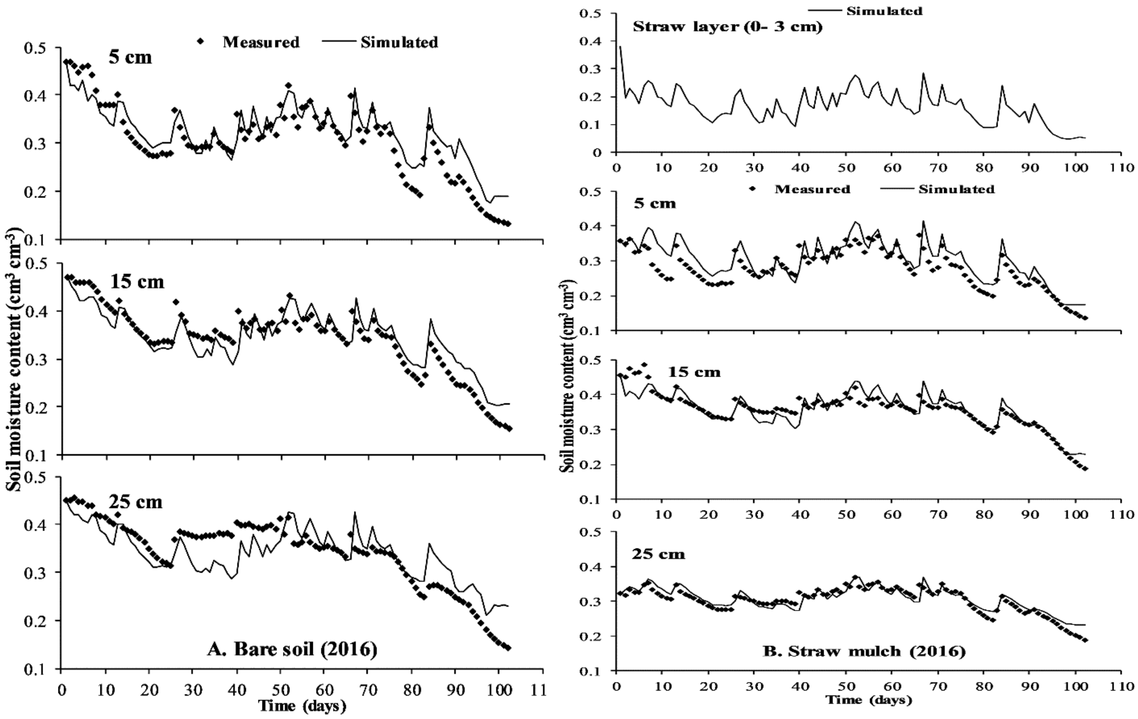

Figure 7.5 Simulated and measured daily soil moisture contents at 5, 15 and 25 cm depths under (A) bare soil and (B) straw mulch treatments during the soybean growing season of 2016.

The simulated moisture content of the straw layer is lower compared to the three soil layers (**Figs. 7.4** (B) and **7.5** (B)). The straw layer absorbed substantial quantity of water during rainfall and drained water more quickly than the soil profile. In 2015, soil moisture content varied from 0.14 to 0.43 cm^3 cm^{-3} under the two treatments; the straw layer contained 0.09 to 0.32 cm^3 cm^{-3} water. Similarly, soil moisture content varied from 0.11 to 0.48 cm^3 cm^{-3} and straw layer contained 0.07 to 0.43 cm^3 cm^{-3} water in 2016. A higher fluctuation trend of soil moisture was observed in 2015 than in 2016 due to higher rainfall in 2015 (**Fig. 7.1**). As illustrated in **Figs. 7.4** (B) and **7.5** (B), the straw layer initially

Table 7.5 Performance of HYDRUS-1D in simulating soil moisture content of the bare soil and straw mulch treatments in terms of Root Mean Square Error (*RMSE*, cm^3 cm^{-3}) and coefficient of determination (R^2) during the soybean cultivation periods of 2015 and 2016.

Treatments	Depth	2015		2016	
	(cm)	*RMSE*	R^2	*RMSE*	R^2
Bare soil	0–10	0.038	0.799	0.036	0.854
	10–20	0.027	0.889	0.030	0.843
	20–30	0.018	0.914	0.044	0.654
Straw mulch	0–10	0.037	0.629	0.036	0.759
	10–20	0.028	0.672	0.026	0.772
	20–30	0.027	0.628	0.016	0.829

provided greater water content than the soil since higher moisture content was set at the beginning of simulation due to wetting of the straw mulch.

7.3.3 Water consumption of straw and soils

A comparison of the measured and simulated soil water consumptions, *SWC*s, in 0–30 cm rooting zone of the two treatments is provided in **Table 7.6**. The rate of daily mean *SWC* of the bare soil was greater than that of the straw-mulched soil for both the measured and simulation periods of 2015 and 2016. Simulation result shows that bare soil consumed 2.84 to 6.22 mm water daily from 0–30 cm rooting zone, whereas the straw-mulched soil consumed 2.81 to 5.45 mm water per day. The 0–3 cm straw layer consumed a daily average of 1.20 mm water in 2015 and 0.57 mm in 2016 (**Table 7.6**). The simulated *SWC* was larger in bare soil than in mulched soil. The straw mulch did not only alter distribution of water consumption by evaporation from straw layer, but also reduced it from the mulched soil. In the bare soil, evaporation rate was high since it occurred directly from the soil surface, but the straw mulch protected soil surface and evaporation occurred from the straw materials, which reduced soil evaporation and, consequently, *SWC*. The simulated *SWC* was higher in 2015 than in 2016 due to greater amount of rainfall in 2015 than in 2016.

In 2015, *SWC* from 0–30 cm soil profile was higher (5.45 mm d^{-1}) due to greater *SWC* by the straw layer; *SWC* was smaller in 2016 for both the soil and straw layers (**Table 7.6**) due to low rainfall in that year. Clearly, the application of organic mulch, compared to bare soil, considerably protected the soil water from being consumed. The straw mulch enhanced evaporation from 0–3 cm mulch layer and, consequently, reduced soil water consumption rates by retaining soil moisture in the root zone.

Table 7.6 Difference between measured and simulated soil water consumptions (*SWC*, mm d^{-1}) of the bare soil and straw mulch treatments during the soybean cultivation periods of 2015 and 2016.

Events	*SWC* in 2015					*SWC* in 2016				
	Bare soil		Mulched soil		Straw layers	Bare soil		Mulched soil		Straw layers
	M	S	M	S		M	S	M	S	
1	5.62	7.23	1.35	4.90	1.65	4.22	2.80	3.27	3.13	0.57
2	4.29	5.78	1.2	4.02	1.07	2.07	3.04	1.76	3.23	0.53
3	5.85	5.24	2.49	10.55	2.27	2.03	2.91	1.29	2.15	0.67
4	1.17	7.60	0.97	3.15	0.17	1.84	3.19	2.04	3.36	0.64
5	7.57	5.24	1.28	5.26	0.98	2.56	2.64	1.95	2.71	0.53
6	4.78	6.22	1.01	4.83	1.05	2.56	2.47	2.58	2.30	0.47
Average	**4.88**	**6.22**	**1.38**	**5.45**	**1.20**	**2.55**	**2.84**	**2.15**	**2.81**	**0.57**

M: Measured and S: Simulated.

7.3.4 Soil temperature

Figures 7.6 (A, B) and **7.7** (A, B) illustrate temporal variation of the measured and simulated daily average soil temperatures at 5, 15 and 25 cm depths in the two treatments (bare and mulched soils) during the soybean growing season of 2015 and 2016. The pattern of estimated temperature of the straw layer is depicted in **Figs. 7.6** (B) and **7.7** (B). Soil temperature fluctuated greatly (18 to 29°C) in the upper 5-cm layer compared to the deeper layers (15 and 25 cm) in both treatments. The differences between simulated and measured soil temperatures may be partially attributed to the specified boundary conditions of the simulation models. In both crop years, R^2 was fairly large (0.81 to 0.97) for both treatments (**Table 7.7**). *RMSE* was 0.97–1.57°C for bare soil and 0.94–1.63°C for straw-mulched soil during the two years' simulation periods (**Table 7.7**). The model provided consistently large *RMSE*s (1.7 to 3.1°C) in simulating soil temperature; similar *RMSE* in simulating soil temperature by HYDRUS model was also found and investigated by Deb et al. (2013). Due to the lack of directly measured thermal conductivity and volumetric heat capacity of the experimental soil, their standard values were optimized by inverse simulation by using the models of Chung and Horton (1987) and de Vries (1963) (**Table 7.4**). Variations of the optimized thermal conductivity and volumetric heat capacity over the moisture

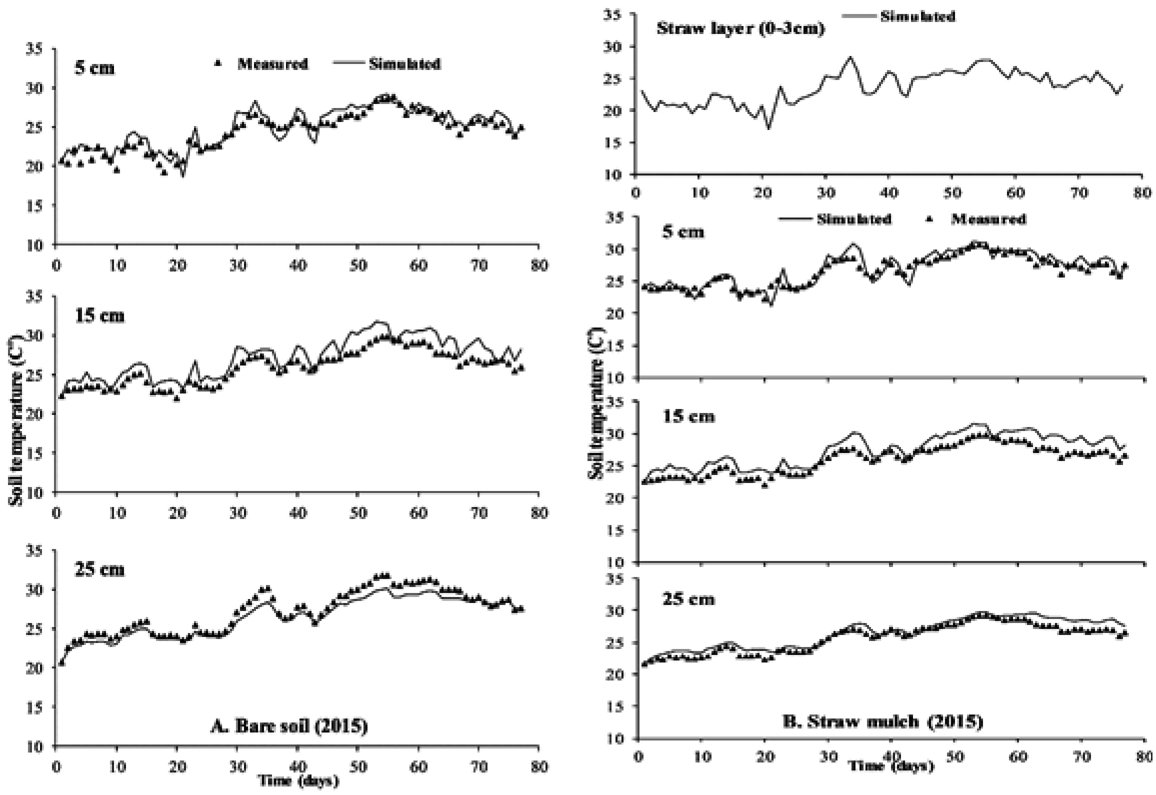

Figure 7.6 Simulated and measured daily soil temperatures at 5, 15 and 25 cm depths under two treatments of (A) bare soil and (B) straw mulch during the soybean growing period of 2015.

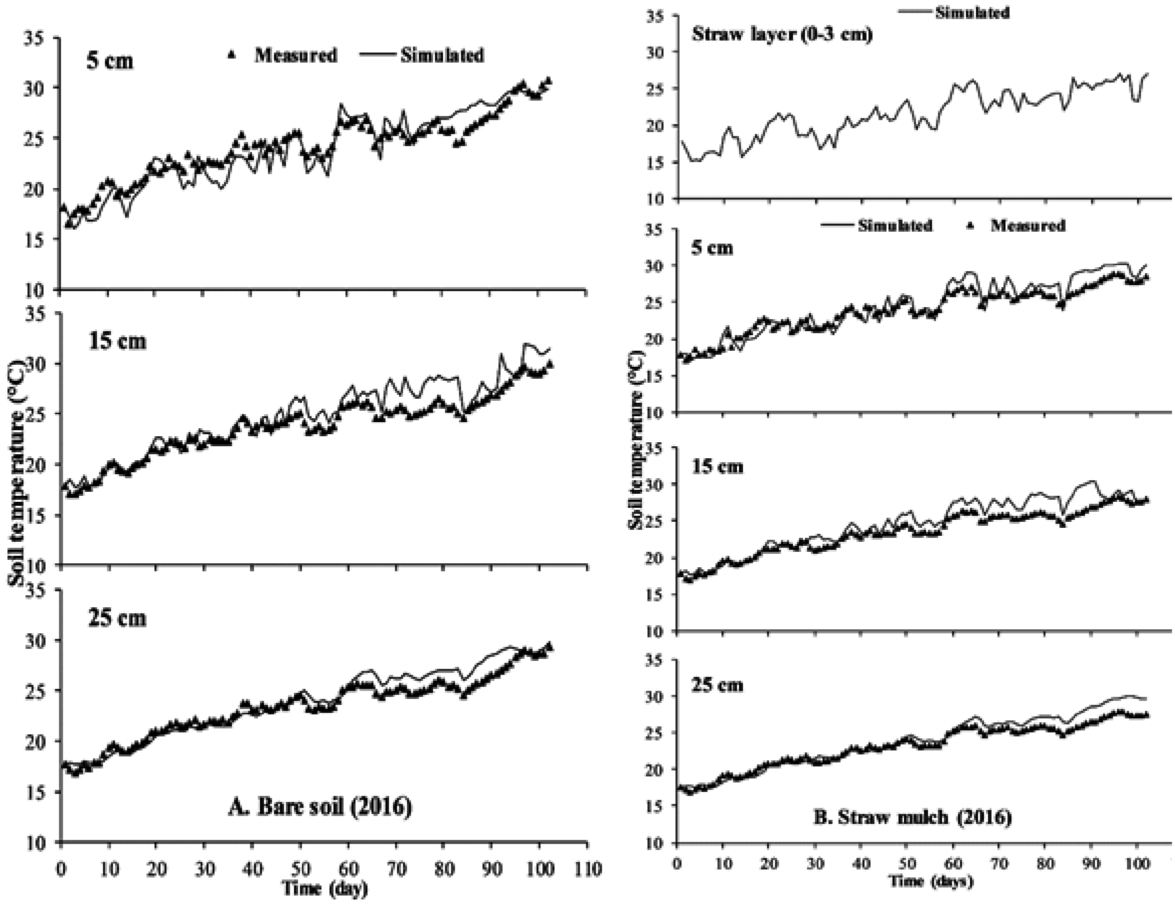

Figure 7.7 Simulated and measured daily soil temperatures at 5, 15 and 25 cm depths under two treatments of (A) bare soil and (B) straw mulch during the soybean growing period of 2016.

contents for the soil and straw layers are illustrated in **Fig. 7.8**. Both the thermal conductivity and volumetric heat capacity were lower in straw mulch than in soil layers (**Fig. 7.8**). These results are in agreement with Kodesová et al. (2013). The accuracy of the optimized heat transport parameters (**Table 7.4**) and the effects of the specified surface and bottom heat transport boundary conditions may be the possible reasons for deviations between the observed and simulated soil temperatures. Moreover, the emergence of soybean leaf canopies over time might also have contributed to increase the simulated soil temperature. In this study, we optimized a limited number of heat transport parameters using HYDRUS-1D model that made several approximations enough to simulate soil temperature at three soil layers and one straw layer.

Table 7.7 Performance of HYDRUS-1D in simulating soil temperature at three different depths under bare soil and straw mulch treatments in terms of Root Mean Square Error (*RMSE*, °C) and coefficient of determination (R^2) during the soybean cultivation periods of 2015 and 2016.

Treatments	Depth	2015		2016	
	(cm)	*RMSE*	R^2	*RMSE*	R^2
Bare soil	0–10	1.21	0.81	1.39	0.89
	10–20	1.57	0.90	1.48	0.93
	20–30	0.97	0.97	0.98	0.96
Straw mulch	0–10	1.15	0.82	1.32	0.92
	10–20	1.63	0.90	1.52	0.94
	20–30	0.94	0.92	1.09	0.97

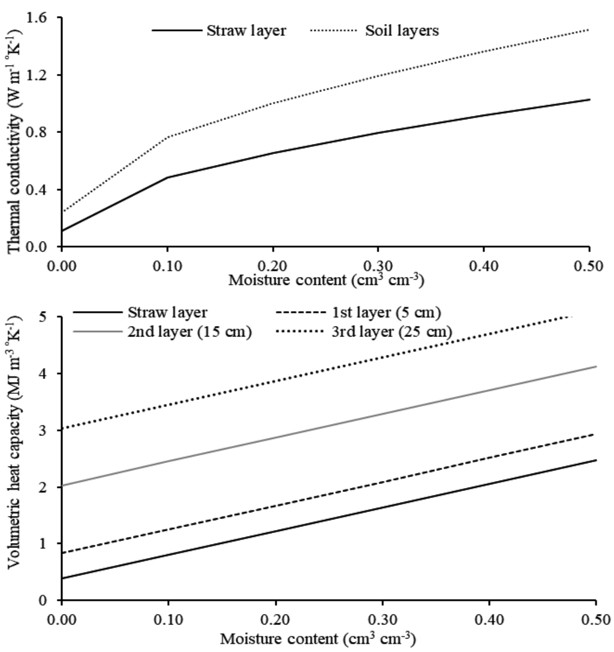

Figure 7.8 Parameters of thermal conductivity and volumetric heat capacity in relation to moisture content for straw and soil layers at the simulation period.

7.3.5 Vapor and liquid water transport

HYDRUS-1D model calculated the amount of vapor in the straw and soil layers during two drying periods of 18th and 31st days in 2015 and 21st and 82nd days in 2016 (**Table 7.8**). Vapor ratio is the total vapor (thermal and isothermal vapor) flow to the total water flow in the nodes of soil profile, while liquid flow is the sum of isothermal liquid flow and thermal liquid flow. In the top 0–10 cm soil and straw mulch (0–3 cm) layers, a rapid change of vapor occurred that influenced water and heat transport mechanisms as well as total water and heat fluxes through the soil profile. The isothermal vapor flow

Table 7.8 Vapor ratio and liquid flow (cm d^{-1}) at different soil and straw layers of the bare soil and straw mulch treatments at two drying days during the experimental periods of 2015 and 2016.

Treatment	Layers	Depth (cm)	Vapor ratio	Liquid flow	Vapor ratio	Liquid flow
			Dry 1 (Day 18)		Dry 2 (Day 31)	
Bare	1st soil	0–10	0.037	0.133	0.089	0.136
(2015)	2nd soil	10–20	0.001	0.188	–0.000	0.260
	3rd soil	20–30	–0.001	0.092	-0.002	0.241
Straw	Straw	0–3	0.466	0.111	0.961	0.010
(2015)	1st soil	0–10	0.023	0.235	0.074	0.171
	2nd soil	10–20	–0.000	0.203	–0.002	0.372
	3rd soil	20–30	–0.001	0.105	–0.001	0.435
			Dry 1 (Day 21)		Dry 2 (Day 82)	
Bare	1st soil	0–10	0.113	0.059	0.052	0.185
(2016)	2nd soil	10–20	–0.002	0.157	–0.004	0.232
	3rd soil	20–30	–0.002	0.205	–0.006	0.221
Straw	Straw	0–3	0.163	0.046	0.529	0.069
(2016)	1st soil	0–10	0.008	0.001	0.083	0.098
	2nd soil	10–20	–0.001	–0.000	–0.002	0.156
	3rd soil	20–30	–0.001	–0.000	–0.003	0.165

is very small and hence was neglected in the calculations. The straw mulching contributed 16.31–96.12% vapor to total water flow, indicating that major portion of the vapor transported to atmosphere from the 0–3 cm straw layer (**Table 7.8**). The vapor ratio of different soil layers of the two treatments varied over 0–8.87% during the 18th and 31st drying days in 2015 and 0–11.24% during the 21st and 82nd drying days in 2016 (**Table 7.8**). Consequently, the liquid water flow varied from 0.01 to 0.465 cm d^{-1} in 2015 and 0 to 0.528 cm d^{-1} in 2016 under the three soil layers and straw layer. The liquid water flow in soil influenced the total water flow during drying of the soil both before and after rainfall events. The effect of vapor was not significant at rainy days and may be ignored. During the drying period, vapor flow occurred mostly from the upper soil and mulch layer (Deb et al., 2010; Yang et al., 2012). The rough-shaped structure of the straw materials maintained greater porosity than the soil, implying that water movement was dominated by vapor phase from the mulch. This phenomena, as reported by Findeling et al. (2003), protects the soil from incoming radiation. Therefore, dryland cultivations with mulching, vapor transport can play a vital role in the exchange phenomena among the soil, water and atmosphere.

6.3.6 Field water balance

Water balance in the HYDRUS-1D modeling with cumulative water fluxes in and out of the simulation flow domain is described for the entire growing season and also for selected wetting to drying periods in **Table 7.9**. The components in the process of water balance included rainfall, runoff, evaporation, plant transpiration and change in soil water content at all nodes of the soil profile (153 cm, including straw mulch). The actual surface flux, defined as infiltration minus runoff and evaporation, is an important parameter of water balance. The storage changes in water balance are defined as the total cumulative value of actual surface flux minus transpiration and bottom fluxes. The cumulative infiltration, evaporation and runoff were higher under straw treatment, which showed smaller storage compared to bare soil for the entire growing season (**Table 7.9**). Straw materials with greater hydraulic conductivity compared to soil caused greater infiltration during rainfall periods. The rainwater within the straw material and topsoil layer satisfied a considerable part of atmospheric evaporative demand and helped increasing the root zone moisture content of the mulched treatment. Although, plant transpiration of the two treatments was almost similar in the two crop years, the bottom flux was higher for the bare soil due to predominant vertical water movement in the deeper soil layers below root zone.

For clear understanding, soil water balance in the two treatments was calculated for a selected wetting to drying period of 3 days (15 to 18) in 2015 and 8 days (13 to 21) in 2016 corresponding to 98.2 mm and 25.4 mm rainfall. The changes in water storage of soil and straw layer in the entire soil profile (150 cm) were calculated for selected periods at the simulation nodes. The cumulative actual surface flux was larger for the straw treatment than for bare soil both in 2015 and 2016 (**Table 7.9**). The cumulative actual surface fluxes significantly increased under the mulching treatment due to greater infiltration into the straw surface and ultimately transferred to the soil layers. It appears that the 0–3 cm thick straw layer contributed 0.51 cm water to total water consumption in 2015 and 0.38 cm in 2016 (**Table 7.9**). The negative value of soil moisture storage (**Table 7.9**) indicates water loss during the selected periods. The result of water balance reveals that straw layer increased evaporation by increasing actual infiltration, which significantly reduced soil water consumption, *SWC*, as well as water storage of the straw mulched soil.

Table 7.9 Estimated water balance with HYDRUS-1D under straw and bare soil treatments for entire growing season and a selected wetting to drying periods of 15th to 18th days in 2015 and 13th to 21st days in 2016.

Treatments	Infiltration	Evaporation	Runoff	vTop	vRoot	vBot	Storage change
	Total cumulative value (cm)						(cm)
Bare 2015	71.00	5.14	0.20	65.66	32.10	36.30	–2.74
Straw 2015	71.49	6.17	0.45	64.87	32.79	34.35	–2.27
Bare 2016	59.98	3.82	0.16	55.99	36.07	46.04	–26.11
Straw 2016	60.21	7.45	0.47	52.30	35.18	32.98	–15.86

Water balance for a selected wetting to drying period

Treatments	Period	Cum(vTop)	Cum(vRoot)	Cum(vBot)	Storage change	ΔS (cm)		
	(Day)	1	2	3	(1-2-3)	Soil	Straw	Total
Bare 2015	15 to 18	0.03	1.08	5.75	–6.80	–6.90	-	–6.90
Straw 2015		0.46	0.31	5.78	–5.63	–5.47	–0.51	–5.98
Bare 2016	13 to 21	0.01	3.57	3.96	–7.52	–7.58	-	–7.58
Straw 2016		0.35	3.53	3.43	–6.61	–6.49	–0.38	–6.87

Note: vTop: actual surface flux; vRoot: actual transpiration rate; vBot: actual flux at the bottom of soil profile; ΔS: change in soil moisture storage between the periods.

6.3.7 Soil heat storage

Soil heat storage, expressed by the rate of change of heat quantity at each node, was estimated from the temperature change between two specified time periods and volumetric heat capacities. Soil heat storage was calculated for the three soil layers (5, 15 and 25 cm depths) and a straw layer of the two treatments during 15th to 18th days in 2015 and 13th to 21st days in 2016 (**Table 7.10**). Soil heat storage decreased with increasing depth in bare soil due to decreasing rate of temperature change in the deeper soil layers in 2016. The negative sign of heat storage indicates that heat was released toward deeper soil layers due to temporal decrease in temperature in those soil layers. Heat storage of the three soil layers in the two treatments differed in the two crop years: –0.042 to 0.072 MJ m^{-2} d^{-1} in 2015 and 0.112 to 0.158 MJ m^{-2} d^{-1} in 2016 (**Table 7.10**). The 0–3 cm thick straw mulch released 0.032 MJ m^{-2} heat daily during 15th to 18th days in 2015 and stored 0.0295 MJ m^{-2} heat daily during 13th to 21st days in 2016. In addition, the 0–3 cm straw layer stored 10% of heat compared to 0–30 cm soil layers in 2016. Higher heat storage was obtained in 2016 due to greater soil temperature changes between the two days that distributed heat into straw and soil layers.

Table 7.10 Soil heat storage at different soil and straw layers of the bare soil and straw mulch treatments during 15th to 18th days in 2015 and 13th to 21st days in 2016.

Year	Periods (Day)	Layers (cm)	Soil heat storage (MJ m^{-2} d^{-1}) Bare soil	Straw mulch
2015	15th to 18th	Straw (0–3)	-	–0.032
		0–10	–0.071	0.072
		10–20	0.098	0.076
		20–30	–0.042	–0.056
2016	13th to 21st	Straw (0–3)	-	0.030
		0–10	0.158	0.112
		10–20	0.123	0.120
		20–30	0.112	0.116

7.4 Discussion

7.4.1 Modeling implications

The coupling of soil water, heat and vapor flow was simulated using HYDRUS-1D model under mulching by designing an extra layer of rice straw on soil surface. The model can be considered accurate enough to predict water and heat transfer in straw-mulched soil under the complexity of modeling scenarios, such as heterogeneous soil properties, and fluctuation of rainfall, evapotranspiration and root distribution. In HYDRUS, the set of various boundary conditions for mulching was distinguished by several investigators (e.g., Dahiya et al., 2007; Zhao et al., 2010). In previous studies, numerical simulations with HYDRUS under mulching often neglected vapor transport (Kodešová et al., 2014; Chen et al., 2014; Zhao et al., 2018) and heat flow (Chen et al., 2018; Li et al., 2015; Saglam et al., 2017). But, this study considered both vapor transport and heat flow. In our study, HYDRUS provided improved simulations of water flow than heat flow, indicating that soil heat transport parameters are more heterogeneous than hydraulic parameters. The employed initial soil hydraulic functions were adopted from laboratory-measured data, but the heat transport parameters were unknown and hence optimized by inverse simulations (**Tables 7.5** and **7.7**). In addition, out of nine unknown heat transport parameters in HYDRUS, we optimized only three (θ_n, C_o and C_n) values and the other parameters were kept as default for loamy soil (**Table 7.4**). These might cause inferior performance in simulating heat flow. Although, the coupling of HYDRUS-1D with DSST model for soybean crop was reported by Shelia et al. (2018), other combinations of crop yield model like SWAP (Kroes and van Dam, 2003) and AquaCrop (Raes et al., 2009) would be possible to describe the full scenario of soil water plant and atmospheric simulation systems.

7.4.2 Straw mulching effects on water flow

Water flow through the mulched-soil was altered in the presence of straw layer on soil surface. The contact area among the straw surface, air and soil might be influenced by the water flow process under straw mulching. The straw material retained water after rainfall that evaporated rapidly from straw surface during the drying days. **Figure 7.9** demonstrates changes in cumulative water storage during the entire crop growing season of 2015 and 2016. The 0–3 cm thick straw mulch layer contributed to total water flow that reduced the changes in water storage in both crop years (**Fig. 7.9**). The greater amount and number of rainfall events in 2015 resulted in considerable fluctuation of water storage in that year (**Fig. 7.9**). However, the bare soil showed greater changes in storage in both crop years compared to mulching treatment due to smaller actual surface flux, which lead to lower infiltration and greater bottom fluxes (**Table 7.9**). In 2016, the amount of rainfall was relatively small than in 2015. In **Fig. 7.9**, the magnitude of changes in cumulative water storage is smaller under the mulching treatment due to water storage in straw layer, evaporation from straw surface and lower downward water flow. Finally, we conclude that the effects of water storage in straw mulching are highly characterized by rainfall amount and straw thickness. Rainfall was the only input of water balance, where water loss included evaporation from the straw material and soil, transpiration from rooting zone, downward water flow and lateral water movement due to surface runoff. Compared to bare soil, the straw layer contributed higher to vapor flow, which caused greater evaporation from straw mulching. The straw-covered surface reduced infiltration into soil by interception. The reduction of infiltration was a function of type and density of straw, covering area, and intensity and duration of rainfall (Kozak et al., 2007).

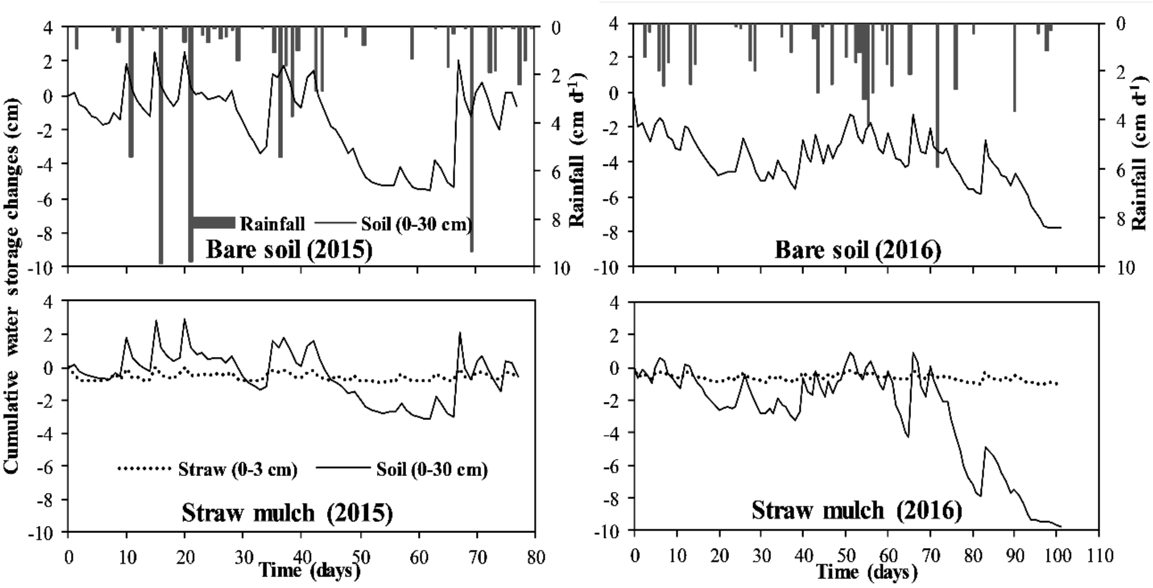

Figure 7.9 Changes in cumulative water storage under straw mulch and bare soil treatments during the soybean growing seasons of 2015 and 2016.

The effects of straw materials reveal that the straw mulch, by reducing evaporation from soil surface and increasing infiltration of rainfall, can improve soil water content.

Probably, the straw mulch layer acted as a buffer medium against rainfall by providing greater porosity and hydraulic conductivity, from which water drained out faster during rainfall and evaporated rapidly at sunny days. These characteristics of straw mulch layer caused smaller water content within the mulch layer, with considerable fluctuations compared to soil layers (**Figs. 7.4** (B) and **7.5** (B)). Kodešová et al. (2014) reported water flow simulations in such coarse grained materials as critical since the covering surface caused water retardation with significantly enhanced evaporation. Rice straw is high-quality natural cellulose that incorporates with soil surface, provides greater pore space within its fibers, and stores large quantity of water for a shorter time period during rainfall events. The straw materials then retain water and transfer it slowly into the soil layers by reducing bottom fluxes. In contrast to an impermeable layer of plastic mulching, which completely restricts water and aeration near the soil surface, straw materials being permeable allow entry of air and water through the straw surface.

7.4.3 Straw mulching effects on heat flow

Suitable soil temperature is an important factor to improve crop growth and yield under straw mulching (Kader et al., 2017b). Soil temperature under straw mulch is variable; it can increase or decrease depending on situations and locations (Pramanik et al., 2015; Zhou et al., 2009). For example, Li et al. (2018) reported that straw mulching showed reducing effect on soil temperature, while plastic film mulch increased soil temperature in a similar experiment. Moreover, straw mulch layer preserved rain water by controlling evaporation loss that also reduced soil temperature due to low thermal conductivity (Ghosh et al., 2006). In addition, soil temperature might be influenced by incoming solar radiation and straw cover that acted as insulator and prevented solar radiation and reduced soil temperature under straw mulching.

Soil heat balance was largely influenced by soil water distribution as well as liquid water and vapor transport in the simulated soil domain. Soil heat storage is highly characterized by volumetric heat capacity and temperature difference between two time periods. It increased cumulatively over time due to increasing air temperature (**Fig. 7.10**). Although the effects of heat storage on 0–3 cm straw layer are relatively small compared to 0–30 cm soil layers (**Fig. 7.10**), straw mulching may have contributed to store heat on its surface. Also, the temperature difference between the two periods and treatments in each crop year being small showed minimum effect of heat storage by straw mulching (**Fig. 7.10**). Temperature decreased in deeper soil layers due to reduced temperature gradient. Heat transfer in the upper soil profile was highly sensitive to fluctuation of soil evaporation and air temperature, while soil temperature at the lower depth was relatively invariant over time. In this study, any influence of the shadow cast by the soybean plants was not considered. The leaves of the crop spread over the treatment plots and might have reduced the temperature effects at the soil surface. However, the extra layer of straw mulch stored heat and transferred it to soil surface and, consequently, reduced temperature of the mulch surface.

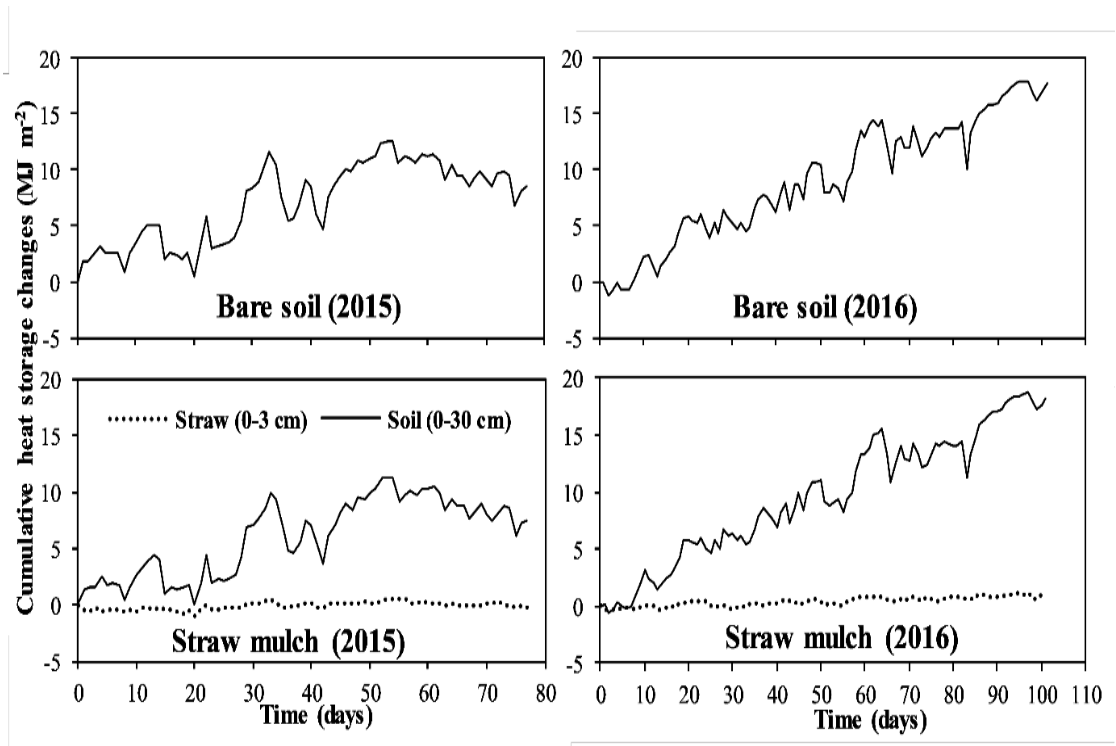

Figure 7.10 Changes in cumulative heat storage under straw mulch and bare soil treatments during the soybean growing seasons of 2015 and 2016.

7.5 Conclusions

We analyzed the characteristics of a rice straw layer on soil surface as one of the materials in the calculation domain of HYDRUS-1D simulation. The HYDRUS-1D model simulated soil water and heat flow regimes at 5, 15 and 25 cm depths in a rainfed soybean field with straw mulching and bare soil treatments during 2015 and 2016 crop seasons. The hydraulic and thermal parameters of the straw mulch were optimized by focusing on vapor flow, heat storage and water consumption characteristics of straw material. The straw mulch, by reducing evaporation from soil surface and increasing rain water infiltration into soil, increased soil water content compared to bare soil. Simulation results show that the bare soil and straw-mulched soil consumed 2.84 to 6.22 mm and 2.81 to 5.45 mm water daily from 0–30 cm rooting zone, whereas the 3-cm straw layer consumed a daily average of 0.57 to 1.20 mm water. The straw mulch contributed 16 to 96% vapor to total water flow, indicating that majority of vapor transported to the atmosphere from the straw layer. The simulation results can be useful for better management of soil hydrothermal regimes under straw-mulched fields in dryland cultivations.

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CHAPTER 8

Summary and conclusions

8.1 Summary of the study

Mulching technique can play an important role to conserve soil water in rainfed crop cultivation. This thesis examined the effectiveness of various mulching materials on soil moisture and temperature regimes from two (2015–2016) years of field experiments under rainfed soybean crop production in central Japan area. Furthermore, numerical simulations using HYDRUS software quantified the characteristics of mulch materials by analyzing soil hydrothermal regimes. The contents of the thesis consist of eight chapters mainly focusing on five published manuscripts. Chapter 2 (review article) describes the extent of influences of different mulching materials and methods on the hydrothermal environment of soils. Chapters 4, 5 and 6 discussed various organic and plastic mulching effects on soil moisture and temperature regimes that influenced soybean growth, yield and productivity. In addition, chapter 7 investigated the numerical simulation of soil water and heat flows under straw mulching soil. Finally, the summary and conclusions (chapter 8) accumulated the highlighted outcome of the thesis and provided future research direction by discussing essential sections. The different mulch materials lower soil water consumptions and regulate soil temperature. These results can be used to minimize water use in rainfed agricultural. The findings of the study are summarized in the next sections.

Management practices related to water saving in rainfed system is essential for sustainable crop production. In this study, we used recycling newspapers as organic mulch that are available and cheap organic materials; these are relatively new and were not investigate yet. Also, locally available organic materials such as rice straw and dry grass were used as mulching and evaluated for their effectiveness in controlling soil moisture and temperature regimes. For inorganic treatment, we selected three-color film (black, silver, and transparent) mulches that are popularly used by farmers in central Japan area. Moreover, we designed a novel film application method "plastic-hole mulch" by cutting extra uniform holes on the film surface rather than crop planting holes for increasing rainwater infiltrations compared to traditional flat plastic mulching. Afterwards, we evaluated the effectiveness of various organic (straw, and newspaper) and plastic (black, silver and transparent, plastic-hole) mulching materials on soil hydrothermal regimes under rainfed soybean crops. Various mulching effects were quantified by introducing new tools of soil water consumption, soil heat accumulation, soil moisture extraction pattern and total readily available water from different soil layers of 0 to 30 cm root zone depths. Moreover, the growth attributes of soybean crops were evaluated by comparing the yield, plant height, leaf chlorophyll content (SPAD value) and nodulation, and water and heat use efficiency among the various mulching and bare soil treatments.

Numerical simulations of water and heat flows give an understanding of how the system works under mulched soil. Therefore, to know how amount of water and heat regimes are modified by mulch in rainfed system are important. We used HYDRUS-1D for straw mulch simulations considering a hypothetical straw layer on soil surface and investigated a couple of vapor, water and heat flows mechanism through soil as well as straw materials. Ultimately, the characteristics of rice straw layer were analyzed by focusing on the amount of vapor flows, water balance, soil water and heat storages of straw as well as soil layers. Simulation results show that the straw mulch layer reduced soil water consumption, soil evaporation, and water storage compared to bare soil. In this study, we did not conduct the economic evaluations of various mulches in respect to soybean production. Because field size of each treatment plot is very small and we used the same film thickness of plastic for each treatment. Therefore, the costs of the various plastic colors were the same. Thus, the economic analysis of yield depends on total production of soybean under each mulch treatment. Although economic evaluation is important, the cost of plastic film and the price of soybean crops are changeable by economic and social conditions of each country and crop year. The results of the analysis of economical parameters cannot show the general effect like quantifications of water and heat regimes. Moreover, as we discussed, the plastic mulching has a lot of short-term benefits on crop productivity and hydrothermal environments, while it has also negative impacts on the soil environment, especially microplastic pollution that is not considered in our study. The more specific outcome from each main chapter has been explained below.

In chapter 4, to investigate the effects of rice straw and newspaper mulching on moisture and temperature regimes of soil, soil water consumption (*SWC*), soil moisture extraction pattern (*SMEP*), total readily available moisture (*TRAM*), water use efficiency (*WUE*) as well as growth and yield of soybean from two years' (2015 and 2016) field experiments were analyzed. Mulching increased seasonal soil moisture content with lesser fluctuations in the root zone compared to bare soil. Both (straw and newspaper) mulching enhanced soil moisture content and water use efficiency and lowered temperature as well as soil water consumption compared to bare soil. Soil moisture extraction was the highest from 0 to 10 cm depth followed by 10–20 cm and 20–30 cm under the (straw, newspaper, bare soil) treatments in both soybean growing seasons. *TRAM* varied among the three (straw, newspaper, bare soil) treatments due to different root distributions and soil characteristics. Although both the organic mulches provided good results, newspaper mulch gave higher seed yield and water use efficiency of soybean by maintaining lower soil temperature, and greater soil moisture compared to straw mulch. Mulching significantly improved plant height, leaf chlorophyll content, nodulations, grain (pod) and seed numbers, biomass, and grain and seed yields of soybean compared to bare soil. Thus, newspaper can be an alternative option to rice straw mulch for improving soil hydrothermal regimes for rainfed soybean cultivation in central Japan area.

Chapter 5 includes the new types of plastic film application method called "plastic-hole mulch" for increasing rainwater infiltration over flat plastic mulching. The comparative performance of plastic, plastic-hole mulching and bare soil were investigated to find the effective rainfall and available soil moisture of rainfed soybean field in the year of 2015. The plastic-hole treatment increased effective rainfall by as much as 9% of total rainfall compared to the plastic treatment. Results of *SMEP* in the 0–30 cm soil profile revealed that soil moisture was consumed, mostly, from the upper soil layer in the bare treatment, while in the plastic and plastic-hole treatments, soil moisture consumption occurred both from the upper and lower soil layers. Consequently, the P and PH treatments provided greater *TRAM* than the bare treatment, indicating that mulching contributed to increasing soil moisture availability in the root zone. As like organic mulch, plastic-hole, plastic mulching lowered soil temperature at 5 cm depth in the experiment year of 2015. Also, both plastic mulch treatments augmented plant height, number of nodulations per plant, and seed and biomass yields; the plastic-hole treatment produced the maximum seed yield. The result suggested that the plastic-hole mulching is a good option for effective utilization of rainfall, increasing soil moisture extraction ratio in the deeper soil layers and increasing total readily available soil moisture for plant growth. However, more research is required on plastic-hole mulching to study the optimal hole numbers, size, and density and long-term sustainability of this mulching which may be beneficial to farmers.

Chapter 6 evaluates the effects of black plastic mulch (BPM), silver plastic mulch (SPM), transparent plastic mulch (TPM) and bare soil on soil temperature regime as well as on growth and yield of rainfed soybean in field experiment 2016. Results revealed a strong correlation between air and soil-surface temperatures in case of bare soil, but weak relationship for various plastic mulching which indicates the colour of the films greatly influenced soil surface temperature beneath the mulches. All color (black, silver and transparent) mulching treatments increased soil temperature compared to bare soil and the magnitude of temperature difference is higher at early growth stages and lower at later growth stages. Among the plastic mulch, black color plastic mulch provided the highest soil temperature at 5, 15 and 25 cm depths that augmented heat accumulation within 0–30 cm rooting zone compared to bare soil, silver and transparent plastic treatments. All colors plastic film mulching reduced soil water consumption (*SWC*) compared to bare soil; the trend of total seasonal *SWC* under the three plastic mulches of different colors was similar. The three-plastic (black, silver and transparent) mulching, by augmenting soil temperature and reducing *SWC* substantially, improved growth and yield of soybean. However, the black color plastic by maintaining the highest soil temperature, provided the highest seed yield of soybean; thus, black film is recommended as suitable plastic mulch for cultivating rainfed soybean in central Japan area.

Chapter 7, simulates the soil water and heat flows by HYDRUS-1D model under rice-straw mulching and bare soil treatments. Soil hydraulic and thermal parameters with the straw mulching were optimized by adding a hypothetical 3-cm straw layer on the calculation domain the HYDRUS model. The optimized parameters were validated with field-measured soil moisture and temperature regimes of two consecutive soybean growing seasons of 2015 and 2016. HYDRUS-1D model performed fairly well in simulating heat and water movements under the two treatments. The simulation results revealed that straw mulching increased soil moisture but reduced soil temperature at the three soil depths compared to the bare soil. The moisture content of the additional straw layer (3 cm) and heat flow through it showed a decreasing pattern compared to the soil layers. Water vapor as well as soil water consumption were analyzed from both soil and straw mulch layers. The straw mulching contributed significant amount of vapor to the total water flow and stored/released soil heat at 0–3 cm straw layer. The straw layer significantly reduced soil water consumption and water storage of straw-mulched soil. Thus, the simulation study can be used for various organic mulch materials to understand the hydrothermal scenarios of mulched-soils.

8.2 Conclusions and future research

The overall conclusions and future research directions are described as follows:

Chapter 4

- Newspaper mulch provided higher yield and water use efficiency of soybean by maintaining lower soil temperature and soil water consumption, and greater soil moisture compared to straw mulch. Thus, newspaper can be an alternative option to rice straw mulch for improving soil hydrothermal regimes for rainfed soybean cultivation in central Japan area.

Chapter 5

- Plastic-hole mulch utilizes lower amount of effective rainfall than bare. Plastic-hole mulching might be the best way to increase rainfall infiltration of traditional flat plastic mulching.
- Further research may be useful to optimize the best density of holes in the plastic mulching by scenario analysis using numerical models for enhancing soil moisture conservation under different climatic conditions.

Chapter 6

- Colored plastic mulching can play a vital role where soil temperature needs to be boosted up for improving soil thermal regime suitable for crop production. Black color is recommended as suitable plastic mulch for cultivating rainfed soybean in central Japan area.
- Moreover, different plastic colors of mulching show different optical properties; thus, mulch color may influence soil temperature and canopy distribution of plants, which need to be numerically simulated in future study.

Chapter 7

- We investigated the characteristics of a rice straw layer on soil surface as one of the materials in the calculation domain of HYDRUS-1D model and simulated soil water and heat flow regimes at 5, 15 and 25 cm depths in a rainfed soybean field with straw mulching and bare soil treatments during 2015 and 2016 crop seasons.
- However, further research with HYDRUS-1D model is needed by covering different organic materials to assess the scenario of mulching with altered plant root water uptake systems under various crops and climates. For example, the modeling effects of vapor flow rate and heat transfer process through organic mulched soil, with various mulch thickness, in response to crop growth in different climatic regions may have an attention in future research.

Table 8.1 Comparative performance evaluation of analyzed parameters in the different mulching treatments in 2015 and 2016.

Year	Mulch treatments	θ	*SWC*	*ER*	*TRAM*	*ST*	*CH*	*WUE*	*Yield*
2015	rice straw	** ↑	↓		↑	** ↓	-	* ↑	** ↑
	newspaper	* ↑	* ↓		*** ↑	* ↓	-	** ↑	* ↑
	silver plastic	↑	-	* ↓	* ↑	↓	-	-	↑
	plastic-hole	↑	-	** ↓	** ↑	*** ↓	-	-	*** ↑
	bare soil				Control				
2016	rice straw	** ↑	↓	-	↑	↓	-	↑	↑
	newspaper	* ↑	↓	-	* ↑	↓	-	↑	** ↑
	silver plastic	↑	*** ↓	-	-	*** ↑	** ↑	↑	↑
	black plastic	↑	** ↓	-	-	* ↑	* ↑	** ↑	* ↑
	transparent plastic	↑	* ↓	-	-	** ↑	*** ↑	* ↑	*** ↑
	bare soil				Control				

Note: θ: Soil moisture content; *SWC*: Soil water consumption; *ER*: Effective rainfall; *TRAM*: Total readily available moisture; *ST*: soil temperature; *CH*: Cumulative heat; *WUE*: Water use efficiency and *Yield*: Soybean seed yield. * indicate the best performance rank followed by ** and *** over the year.

In this thesis, the characteristics of various mulching were evaluated by analyzing the effects of soil hydrothermal regimes. The comparative performance evaluation of different parameters under various mulching treatments is summarized in **Table 8.1**. The mulching materials showed a different pattern of soil temperature due to changing meteorological conditions over the year, while all mulch materials increased soil moisture content at various soil depths compared to bare soil (**Table 8.1**). Our finding revealed that most organic mulch treatments lowered soil temperature more than by plastic mulch and bare soil. Black plastic mulch gave higher yield followed by newspaper mulch and other organic mulch treatments. In addition, applications of various mulching in the soybean field significantly increased the different growth characters such as biomass, plant height and number of nodulations, leaf chlorophyll compared to bare soil treatment. However, all plastic mulch with different colors film increased soil temperature in the experiment of 2016. Also, the plastic mulch performed best in reducing soil water consumption and increasing *WUE*, while the newspaper mulch was good for retaining soil moisture and lowering soil temperature. Among the plastic treatments, transparent color mulch showed the lowest *SWC* followed by black and silver color mulch. *SWC* of organic mulch is always higher than plastic mulch that indicates the plastic mulch restricted lower soil evaporation than organic mulch. However, the plastic-hole mulch increased the utilization of rainfall by enhancing water availability in the soil root zone than plastic mulch without extra-holes. Numerical simulation result showed that the straw mulch, by reducing evaporation from soil surface and increasing rain water infiltration into soil, increased soil water content compared to bare soil. Therefore, in order to get maximum benefit from mulching, it is necessary to investigate the effects of different mulching materials under various field conditions for the best fit of the materials to the crop and climate. Moreover, film color of plastic mulch and application rate of the organic mulch are highly influenced by the selection of mulching material that absolutely depends on farmers' choice. In addition, before recommending the various mulch, it is essential to know the purposes of using in the field conditions for the best fit of the materials to the crop and climate. Therefore, it is concluded that use of various mulching materials can save and conserve water resources in agricultural field and leads to enhance crop yields.

Appendixes

Appendix 1 List of various devices and their orientations in the experimental field for data measurement in the year of 2015.

Logger (number)	Sensor	Depth (cm)	Location	Measured	Manufacturer
Em50 (1)	5TM (1)	5	Straw	VWC & ST	Decagon Devices Inc., USA
	5TM (2)	15	Straw		
	5TM (3)	25	Straw		
	5TM (4)	5	SPM		
	5TM (5)	15	SPM		
Em50 (2)	5TM (6)	25	SPM		
	5TM (7)	5	PHM		
	5TM (8)	15	PHM		
	5TM (9)	25	PHM		
CR10X (1)	CS615 (TDR 1)	5	Bare	VWC	Campbell Scientific Inc., USA
	CS615 (TDR 2)	15	Bare		
	CS615 (TDR 3)	25	Bare		
	CS615 (TDR 4)	5	Paper		
	CS615 (TDR 5)	15	Paper		
	CS615 (TDR 6)	25	Paper		
	PCM-01 (1)	-	Field	solar radiation	PREDE Co. Ltd., Japan
U12-008 (1)	TMC20 (2)	5	Bare	ST	Onset Computer Corporation, USA
	TMC20 (3)	15	Bare		
	TMC20 (4)	25	Bare		
U12-008 (2)	TMC20 (5)	5	Paper		
	TMC20 (6)	15	Paper		
	TMC20 (7)	25	Paper		
RG3-M (1)	Rain gauge (1)	-	Field	Rainfall	
TR-73U (1)	TR (1)	-	Field (2 m height)	AT & RH	T & D Corporation, Japan

TDR: Time domain reflectometer, VWC: Volumetric water content, ST: Soil temperature, TR: Thermo Recorder, AT: Air temperature, RH: Relative humidity, SPM: Silver plastic mulch and PHM: Plastic-hole mulch.

Appendix 2 List of various devices and their orientations in the experimental field for data measurement in the year of 2016.

Logger (number)	Sensor	Depth (cm)	Location	Measured	Manufacturer
Em50 (1)	5TM (1)	5	SPM	VWC & ST	Decagon Devices Inc., USA
	5TM (2)	15	SPM		
	5TM (3)	25	SPM		
	5TM (4)	5	BPM		
	5TM (5)	15	BPM		
Em50 (2)	5TM (6)	25	BPM		
	5TM (7)	5	TPM		
	5TM (8)	15	TPM		
	5TM (9)	25	TPM		
CR10X (1)	CS615 (TDR 1)	5	Bare	VWC	Campbell Scientific Inc., USA
	CS615 (TDR 2)	15	Bare		
	CS615 (TDR 3)	25	Bare		
	CS615 (TDR 4)	5	Paper		
	CS615 (TDR 5)	15	Paper		
	CS615 (TDR 6)	25	Paper		
	CS615 (TDR 7)	5	Straw		
	CS615 (TDR 8)	15	Straw		
	CS615 (TDR 9)	25	Straw		
	PCM-01 (1)	-	Field	solar radiation	PREDE Co. Ltd., Japan
U12-008 (1)	TMC20 (1)	0	Bare	ST	Onset Computer Corporation, USA
	TMC20 (2)	5	Bare		
	TMC20 (3)	15	Bare		
	TMC20 (4)	25	Bare		
U12-008 (2)	TMC20 (5)	0	SPM		
	TMC20 (6)	0	BPM		
	TMC20 (7)	0	TPM		
U12-008 (3)	TMC20 (8)	0	Paper		
	TMC20 (9)	5	Paper		
	TMC20 (10)	15	Paper		
	TMC20 (11)	25	Paper		
U12-008 (4)	TMC20 (12)	0	Straw		
	TMC20 (13)	5	Straw		
	TMC20 (14)	15	Straw		
	TMC20 (15)	25	Straw		
RG3-M (1)	Rain gauge (1)	-	Field	Rainfall	
TR-73U (1)	TR (1)	-	Field (2 m height)	AT & RH	T & D Corporation, Japan

TDR: Time domain reflectometer, VWC: Volumetric water content, ST: Soil temperature, TR: Thermo Recorder, AT: Air temperature, RH: Relative humidity, SPM: Silver plastic mulch, BPM: Black plastic mulch and TPM: Transparent plastic mulch.

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