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Combined application of photo-selective mulching films and beneficial microbes affects crop yield and irrigation water productivity in intensive farming systems

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ABSTRACT

Cultivation of vegetables under plastic tunnels is a steadily growing farming system, nevertheless there are concerns about its environmental sustainability. This work tests a new cultivation system based on the application of photo-selective mulching films to the soil combined with beneficial microbes to improve crop yield, save irrigation water and enhance crop irrigation water productivity. A two-year project was carried out in three farms of southern Italy that practice cultivation in greenhouses with different soil characteristics. Photo-selective mulching films (PS) were used alone or in combination with microbial consortia (M) containing beneficial microbes (i.e. antagonistic fungi of the genus *Trichoderma*, mycorrhizal fungi of the genus *Glomus* and the plant growth promoting bacterium *Bacillus subtilis*) and compared with black plastic mulching (B). Soil temperature, soil water content, and irrigation water volumes were continuously monitored for eight cropping cycles including tomato, sweet pepper, lettuce, melon, and kohlrabi. Crop yields were assessed at the end of each cycle. PS films in combination with M significantly increased crop yields with respect to control, with the most positive effects on winter crops. Soil temperature under PS was consistently lower than that under B mulch. All mulching films allowed the saving of irrigation water compared with untreated control, but no difference was detected between PS and B. However, PS increases crop irrigation water productivity (CIWP) compared with B film in 25% of the experimental cases. In conclusion, our results indicate that combining PS films with beneficial microbes in cultivation under plastic tunnel greenhouses promotes crop yield and increases CIWP compared with control in 87.5% and 75% of the study cases, respectively.

1. Introduction

In recent years major droughts have occurred on almost every continent, including Europe in 2003 (Fink et al., 2004) and the US in 2012 (Boyer et al., 2013), with a negative impact on agriculture and society (Sheffield and Wood, 2011). Agriculture accounts for about 70% of the world's freshwater use, thus exceeding industrial and civilian use (Gleick and Ajami, 2014) and, as a consequence of growing requirements of the human population, competition for freshwater among such economic sectors is becoming more intense (Koehler, 2008). Moreover, the greenhouse effect will reinforce this trend because of the predicted rise of temperatures and induction of longer drought periods (Teixeira et al., 2013). Modern agriculture should implement sustainable systems that reduce water use and, at the same time, increase crop yield. Achieving this goal is difficult, especially for irrigated, intensive agricultural systems that require large amounts of water.

Cultivation under plastic tunnels is a growing agricultural sector with about 2 million ha in the world and more than 190,000 ha in the Mediterranean Basin (Pardossi et al., 2004; Scarascia-Mugnozza et al., 2011). This cultivation system provides several advantages due to the improvement of microclimatic conditions, relatively low investment costs, and high-quality crop yields that provide high net incomes for farmers (Belasco et al., 2013; Bonanomi et al., 2014). However, such a system, because it does not benefit from rainfall

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requires large volumes of irrigation water, ranging from 4000 to 10,000 m^3 ha^{-1} $year^{-1}$.

In order to improve crop water productivity, many researchers are focusing their attention on finding solutions for reducing and optimizing agricultural water use. This is possible by developing more efficient irrigation systems (El-Wahed and Ali, 2013), using new generation materials (Bourzac, 2013), and combining new knowledge into innovative agronomic techniques (Boari et al., 2015). Soil mulching with black plastic films is widely used for reducing water loss by evaporation from the soil surface and controlling weeds (Lament, 1993; Steinmetz et al., 2016). In recent years, the use of photo-selective (PS) mulching films in agriculture was proposed because of their positive effect on photosynthesis and crop yield (Shiukhy et al., 2015), fruit phytochemical quality (Layne et al., 2001), and indirect protection from pests (Ben-Yakir et al., 2013). In addition to such positive effects, PS mulching films, thanks to their high level of reflectivity (Mormile et al., 2012), are potentially capable of keeping the soil cooler, compared with soil covered with conventional black mulch. Consequently, PS mulching films can potentially reduce crop water requirements by means of two complementary mechanisms: reducing direct evaporation from the soil and increasing root efficiency by creating a favorable microclimate in the root-zone.

Recent studies suggest that soil microbes living in the rhizosphere can affect crop tolerance to water stress, and selective manipulation of such microbiome may improve plant water use (Marasco et al., 2012; Zolla et al., 2013). Vesicular-arbuscular mycorrhizal fungi (VAM) are the most widespread underground symbionts of plants (Smith and Read, 1997), and they play a crucial role for plant mineral nutrition and water up-take in natural (van der Heijden et al., 1998) as well as in agro-ecosystems (Den Herder et al., 2010). The increased functional efficiency of plant root infected with mycorrhizal fungi is mainly due to the presence of an extra-radical hypha network of mycorrhizal fungi that, extending into the soil, increase the soil volume explored by roots. In addition, hypha are far more effective than roots in acquiring soil resources and competing with soil free-living microorganisms. Previous investigations have mainly focused on the capacity of these fungi to increase plant mineral nutrition. Special attention has been paid to phosphorus and nitrogen mineral nutrition, looking at VAM fungi as a possible alternative to mineral fertilizers. Instead, the role of mycorrhizas in modifying plant water relations, although relevant, has received less attention (Augé, 2001), probably because the economic benefits are less easily quantified and appreciated. In addition to VAM fungi, other beneficial microbes can be used to improve plant water use (East, 2013). Soilborne plant pathogens (e.g. *Rhizoctonia solani* Kühn, *Pythium* spp., *Fusarium* spp., *Verticillium* spp.) causing root and crown rots, wilts, and damping-off are major yield-limiting factors in agro-ecosystems. Their activities strongly reduce root system development and functions, and consequently diseased plants require a larger amount of water. These pathogens are especially important for protected cultivation under plastic tunnel and their control is difficult and expensive with chemical fungicides. In this context, beneficial fungi and bacteria such as *Trichoderma* spp., *Pseudomonas* spp. and *Bacillus* spp. among others, may represent an alternative to protect the plant root system from soil-borne pathogens (Haas and Défago, 2005; Domenech et al., 2006; Raaijmakers et al., 2009). The application of beneficial microbes can indirectly increase water use efficiency by controlling soilborne pathogens. However, strong evidence that microbial consortia can be used to effectively save irrigation water in field conditions is still lacking.

This work evaluates the capability of PS films and beneficial microbial consortia (M), individually and in combination, to improve vegetable yield and increase crop irrigation water productivity, defined as the ratio of the crop dry biomass to the applied irrigation water volume. Two-year field experiments were carried-out in southern Italy on crops cultivated under plastic tunnels in three farms with contrasting soil characteristics. We measured crop yields, soil microclimate (i.e. temperature and water content) and irrigation water use for eight cropping cycles, including tomato, sweet pepper, lettuce, melon, watermelon, and kohlrabi. The specific hypotheses of this study are: (1) PS will reduce water consumption compared with black mulch by improving soil microclimate; (2) application of M will increase plant growth and enhance crop irrigation water productivity; (3) the combined application of PS film and M, because of their complementary effects, will further increase crop yields and crop irrigation water productivity compared with individual treatments.

2. Material and methods

2.1. Study sites description

The study sites are located in the Salerno district (southern Italy) within a productive area with more than 5000 ha cultivated under greenhouses. Low-technology, unheated polyethylene-covered greenhouses (height 4–5 m) are the main crop protection structures used in this area (Fig. S1). The study site has a Mediterranean climate with a mean annual temperature of 15.9 °C and mean monthly temperatures ranging from 23.6 °C in August to 9.0 °C in January. The climate has a mean annual rainfall of 988 mm with a relatively dry summer (84 mm).

Three farms, hereafter named F1, F2 and F3 (F1 = 40° 34′ 34.67″ N, 14° 59′ 37.69″ E, elevation 41 m a.s.l.; F2 = 40° 59′ 57.89″ N, 14° 19′ 00.89″ E, elevation 24 m a.s.l.; and F3 = 40° 26′ 15.31″ N, 14° 59′ 45.54″ E, elevation 11 m a.s.l.; Fig. S1), were selected among a group of 20 farms that were characterized in a previous study to monitor the effects of plastic tunnel farming systems on soil quality (Bonanomi et al., 2011). In all farms, an intensive cultivation system was previously adopted for at least 5 years based on repeated soil disinfestation treatments (*i.e.* solarization and application of Metham-Na), use of mineral fertilizers by fertigation and an intensive tillage regime with an average of 6 rototilling treatments per year. Some soil properties relevant to irrigated crop management are provided in Table 1. F1 has a clay-loam soil with low limestone

Table 1
Physical, chemical and hydrological properties of F1, F2 and F3 soils at the beginning of the experimental activity.

Parameter	F1	F2	F3
Sand, %	23.48	45.60	23.39
Silt, %	40.14	46.42	30.47
Clay, %	36.38	7.98	46.15
Bulk density, g cm^{-3}	1.46	1.19	1.32
θ_{33} (field capacity)	0.20	0.12	0.25
θ_{1500} (wilting point)	0.11	0.05	0.14
θ_{50}	0.18	0.10	0.23
Electrical conductivity, dS m^{-1}	0.29	0.61	0.25
Limestone, g kg^{-1}	4.89	199.74	302.43
pH	8.07	7.72	8.21
CEC, cmol(+) kg^{-1}	50.74	38.17	40.95
Organic carbon, g kg^{-1}	10.25	13.14	14.03
Total nitrogen, g kg^{-1}	3.10	1.91	3.32
C/N ratio	3.27	7.38	3.97
Nitrate, μg N—NO_{3-} g^{-1}	54.32	45.69	56.78
Ammonium, μg N—NH_{4+} g^{-1}	5.42	3.43	6.45
Microbial carbon biomass, mg g^{-1}	0.152	0.173	0.192
P_2O_5, mg kg^{-1}	205.64	211.78	226.30
Ca^{2+}, $cmol^{(+)}$ kg^{-1}	15.52	18.67	13.82
K^+, $cmol^{(+)}$ kg^{-1}	0.40	0.36	0.43
Mg^{2+}, $cmol^{(+)}$ kg^{-1}	0.96	5.11	1.12
Na^+, $cmol^{(+)}$ kg^{-1}	0.40	0.36	0.43

θ_h: volumetric soil water content at a given matric suction head (h, in kPa).