

1 **Exploring the use of recombinant inbred lines in combination with beneficial**
2 **microbial inoculants (AM fungus and PGPR) to improve drought stress**
3 **tolerance in tomato**

4
5 Mónica Calvo-Polanco^{1,2}, Beatriz Sánchez-Romera¹, Ricardo Aroca¹, María José
6 Asins³, Stéphane Declerck⁴, Ian C. Dodd⁵, Cristina Martínez-Andújar⁶, Alfonso
7 Albacete⁶, Juan Manuel Ruiz-Lozano^{1*}

8
9 ¹Departamento de Microbiología del Suelo y Sistemas Simbióticos. Estación
10 Experimental del Zaidín (CSIC). Profesor Albareda nº 1, 18008 Granada, Spain.

11 ²Current address: Biochimie et Physiologie Moléculaire des Plantes. SupAgro/INRA
12 UMR 5004. 2, Place Viala, 34060 Montpellier Cedex 2, France.

13 ³IVIA, Carretera Moncada-Náquera, km 4.5, Apartado Oficial, 46113 Moncada,
14 Valencia, Spain.

15 ⁴Earth and Life Institute, Applied Microbiology, Mycology, Université Catholique de
16 Louvain, Croix du Sud, 2 box L7.05.06. 1348 Louvain-la-Neuve, Belgium.

17 ⁵Lancaster Environment Centre, University of Lancaster, LA1 4YQ, United Kingdom.

18 ⁶Department of Plant Nutrition, CEBAS-CSIC, Murcia, Spain

19

20 * Corresponding author: Dr. Juan Manuel Ruiz-Lozano

21 Telph. + 34 958181600

22 e-mail: juanmanuel.ruiz@eez.csic.es

23

24

25

26

1 **ABSTRACT**

2 At a world scale, tomato is an important horticultural crop, but its productivity is highly
3 reduced by drought stress. Combining the application of beneficial microbial
4 inoculants with breeding and grafting techniques may be key to cope with reduced
5 tomato yield under drought. This study aimed to investigate the growth responses
6 and physiological mechanisms involved in the performance under drought stress of
7 four tomato recombinant inbred lines (RIL) after inoculation with the arbuscular
8 mycorrhizal (AM) fungus *Rhizophagus irregularis* and the plant growth promoting
9 rhizobacteria (PGPR) *Variovorax paradoxus* 5C-2. Results showed a variation in the
10 efficiency of the different tomato RILs under drought stress and a differential effect of
11 the microbial inoculants, depending on the RIL involved. The inoculants affected
12 plant parameters such as net photosynthetic capacity, oxidative damage to lipids,
13 osmolyte accumulation, root hydraulic conductivity or aquaporin abundance and
14 phosphorylation status. RIL66 was the one obtaining maximum benefit from the
15 microbial inoculants under drought stress conditions, due likely to improved CO₂-
16 fixation capacity and root hydraulic conductivity. We propose that RIL66 could be
17 selected as a good plant material to be used as rootstock to improve tomato growth
18 and productivity under water limiting conditions. Since RIL66 is highly responsive to
19 microbial inoculants, this grafting strategy should be combined with inoculation of *R.*
20 *irregularis* and *V. paradoxus* in order to improve plant yield under conditions of
21 drought stress.

22

23 **Key-words:** arbuscular mycorrhizal symbiosis, drought stress, plant growth
24 promoting rhizobacteria, recombinant inbred line

25

1 **1. Introduction**

2 Drought stress has a major impact on plant growth and development, limiting
3 crop production throughout the world. It has been estimated that nearly one third of
4 soils are too dry to support normal plant development and productivity (Golldack et
5 al., 2014). Moreover, global climate change is spreading this problem of water deficit
6 to regions where drought impacts were negligible in the past (Trenberth et al., 2014).

7 To cope with environmental stresses, plants have developed a variety of
8 strategies (Dobra et al., 2010). Under drought stress plants regulate the permeability
9 of tissues to water movement, use osmotic adjustment and enhance their antioxidant
10 systems. The first of these processes is based on modifying membrane water
11 permeability, a process in which aquaporins are involved (Maurel et al., 2008;
12 Chaumont and Tyerman, 2014). Aquaporins are water channel proteins that facilitate
13 and regulate the passive movement of water molecules down a water potential
14 gradient (Maurel et al. 2015), affecting directly the radial water flow through the cell-
15 to-cell pathway. Under conditions of low transpiration, such as under drought stress,
16 this pathway is predominant for water movement in plants (Steudle and Peterson,
17 1998). Among plant aquaporins, the plasma membrane intrinsic proteins subfamily
18 (PIPs1 and PIPs2) is critical for whole plant water transport (Javot and Maurel, 2002;
19 Chaumont and Tyerman, 2014). Since plants undergo frequent environmental
20 changes, the activity of PIPs must be regulated by mechanisms that allow rapid
21 responses to these changes. Post-translational modifications are necessary to
22 achieve such rapid regulation (Vandeleur et al., 2014), including phosphorylation/de-
23 phosphorylation of specific serine residues, the first post-translational regulation
24 mechanism found in aquaporins. This generates conformational changes allowing
25 aquaporin gating (Johansson et al., 1998; Prado et al., 2013) or modifying the

1 subcellular localization of PIPs in the membrane (Prak et al., 2008) and may be a
2 mechanism to prevent water loss (Bárzana et al., 2015).

3 The accumulation of compounds such as soluble sugars, proline, glycine
4 betaine, pinitol or mannitol allows plants to osmotically adjust to maintain cell turgor
5 (Morgan, 1984; Bheemareddy and Lakshman, 2011). Proline, a non-protein amino
6 acid that accumulates in most plant tissues subjected to water stress, is one of the
7 most common osmolytes accumulated (Kishor and Sreenivasulu, 2014) and can be
8 readily metabolized upon recovery from drought (Singh et al., 2000). Besides acting
9 as an osmoregulatory compound, proline also serves as a sink for energy, regulating
10 redox potentials, as a scavenger of hydroxyl radicals, as a means of reducing acidity
11 in the cell, and as a solute that protects macromolecules against denaturation (Kishor
12 and Sreenivasulu, 2014).

13 Under drought stress, several metabolic pathways are uncoupled and
14 electrons are transferred to molecular oxygen to form reactive oxygen species (ROS)
15 (Noctor et al., 2014). ROS are toxic molecules capable of causing oxidative damage
16 to lipids, proteins and DNA (Miller et al., 2010). However, at low levels, ROS can act
17 as signalling molecules for stress responses and its generation is an early plant
18 stress response (Singh et al., 2011). Antioxidant systems aim to eliminate excessive
19 ROS production under stress conditions (Gill and Tuteja, 2010). The scavenging of
20 ROS is achieved through the action of non-enzymatic compounds and different
21 enzymatic systems. Non-enzymatic mechanisms include compounds able to
22 scavenge directly several ROS, such as ascorbic acid (AsA), glutathione (GSH), or
23 α -tocopherol. Enzymatic antioxidants include superoxide dismutase (SOD),
24 glutathione reductase (GR), catalase (CAT), ascorbate- or thiol-dependent

1 peroxidases, and the enzymes of the ascorbate-glutathione pathway (Scheibe and
2 Beck, 2011).

3 At a world scale, tomato is the most important horticultural crop, and the
4 second most important vegetable consumed after potato. Tomato is a major dietary
5 component in many countries and constitutes an important source of vitamins,
6 sugars, minerals, and antioxidant compounds. However, its productivity is highly
7 reduced by abiotic stresses, including drought (Schwarz et al., 2010). While climate
8 change is reducing crop productivity, world agriculture must increase its productivity
9 by 60% to feed the expected population of 9.6 billion people in 2050 (Cabot et al.,
10 2014). Therefore, drought tolerance is a target trait in breeding programs, particularly
11 for rootstocks. Combining breeding techniques with grafting techniques and the
12 application of beneficial microbial inoculants will play a key role in developing a more
13 profitable horticulture to address this challenge (Asins et al., 2010; Albacete et al.,
14 2015b). The rootstock effect to ameliorate abiotic stress tolerance in tomato was
15 previously tested in a population of recombinant inbred lines (P-RILs) (Albacete et al.,
16 2015a,c).

17 Grafting is a biotechnological tool to improve not only the amount and
18 uniformity of crop yield, but also stress tolerance (reviewed by Albacete et al., 2015b).
19 Nowadays, most fruit crops and many horticultural species are grown as scion-
20 rootstock combinations. This strategy allows desired features such as stress
21 tolerance to be conferred by a suitable rootstock, while retaining excellent fruit yield
22 and quality traits of a given scion (Asins et al., 2010). Thus, to start a grafting
23 program to improve tomato drought tolerance, the selection of suitable genotypes to
24 be used as rootstocks is the first necessary step.

1 Many studies have shown that the arbuscular mycorrhizal (AM) symbiosis and
2 plant growth-promoting rhizobacteria (PGPR) may enhance host plant stress
3 tolerance, including to drought (Azcón et al., 2013; Malusá et al., 2013; Zoppellari et
4 al., 2014). Indeed, plant symbiotic relationships with mycorrhizal fungi greatly
5 increase the surface area over which plant root systems take up water and nutrients.
6 Soil bacteria on the root surface alter root phytohormone status thereby increasing
7 growth, and can make nutrients more available to the plant. Studies have also shown
8 that these beneficial microorganisms improve plant osmotic adjustment and
9 antioxidant responses, as well as, water status throughout regulation of plant
10 aquaporins (Marulanda et al., 2010; Dodd and Ruiz-Lozano, 2012; Azcón et al.,
11 2013; Ruzzi and Aroca, 2015; Kaushal and Wani, 2016). Combining these two
12 groups of microorganisms can increase crop resource use efficiency and
13 productivity under stressful environmental conditions (Dodd and Ruiz-Lozano, 2012).

14 In spite of the positive effects of AM fungi and PGPR on plant productivity, no
15 studies have dealt with the use of breeding techniques in combination with these
16 microorganisms to improve plant productivity under stressful conditions. **Thus, we**
17 **hypothesize that combining the use of a selected group of RILs having specific traits**
18 **with microbial inoculants with a proved ability to improve drought tolerance will be**
19 **useful to combine drought tolerance features coming from both the plant genotype**
20 **and its interaction with AMF and PGPR and, thus, will improve tomato performance**
21 **under drought.** This study aimed to investigate the growth and physiological
22 response of four P-RILs after root colonization by AMF and PGPR. The tomato lines
23 obtaining maximum benefit from the microbial inoculants and performing best under
24 drought stress conditions will be identified and selected as the most suitable in
25 grafting programs directed toward improved tomato productivity under drought. The

1 study also aims to understand the underlying physiological mechanisms involved in
2 the improved plant performance.

3 The RILs used represent a valuable resource that has already been used to
4 identify a specific QTL conferring salinity resistance (Asins et al., 2010, 2015). The
5 AM fungus *Rhizophagus irregularis* DAOM 197198 was formerly known as *Glomus*
6 *intraradices*. It was reassigned to *G. irregulare* by Stockinger et al. (2009) and then
7 as *Rhizophagus irregularis* (Kruger et al. 2012). This fungus is widely used in abiotic
8 stress studies, being one of the most effective in drought stress alleviation (Ruiz-
9 Lozano et al., 2012; Azcón et al., 2013). *Variovorax paradoxus* 5C-2 is a PGPR that
10 promotes tomato root length *in vitro* irrespective of bacterial load (Belimov et al.,
11 2007) and stimulates root and shoot growth of another Solanaceae (potato) grown in
12 both well-watered and drying soils (Belimov et al., 2015).

13

14 **2. Materials and methods**

15 *2.1. Plant materials and experimental design*

16 The experiment consisted of a complete randomized factorial design with four
17 tomato recombinant inbred lines (RIL20, RIL40, RIL66, RIL100) plus one commercial
18 cultivar (Boludo) used as reference (*Solanum lycopersicum* L. cv. Boludo F1,
19 Monsanto). These RILs belong to a population of F10 lines (P population) derived by
20 single seed descendent from a cross between a salt sensitive genotype of *Solanum*
21 *lycopersicum* var. *Cerasiforme* (formerly *L. esculentum*) and a salt tolerant line from
22 *S. pimpinellifolium* L. (formerly *L. pimpinellifolium*) (Monforte et al., 1997). P
23 population has been extensively studied as rootstock of Boludo cultivar to ameliorate
24 tolerance to several abiotic stresses (Albacete et al., 2015a,c; Asins et al., 2015).

1 Plants remained as uninoculated controls or were inoculated either with the
2 AM fungus *Rhizophagus irregularis* MUCL 41833 - DAOM 197198 (AM fungus), the
3 plant growth promoting bacteria *Variovorax paradoxus* 5C-2 (PGPR) or a
4 combination of both microorganisms (AM fungus+PGPR). Ten replicates of each
5 treatment totaled 200 pots (one plant per pot), with half of the plants cultivated under
6 well-watered conditions throughout the entire experiment and the other half subjected
7 to drought stress for four weeks before harvest.

8

9 2.2. Soil and biological materials

10 A loamy soil was collected at the grounds of Instituto de Investigación y
11 Formación Agraria y Pesquera de Andalucía (IFAPA, Granada, Spain), sieved (2
12 mm), diluted with quartz-sand (<1 mm) (1:1, soil:sand, v/v) and sterilized by steaming
13 (100°C for 1 h on 3 consecutive days). The soil had a pH of 8.1 (water); 1.5% organic
14 matter, nutrient concentrations (g kg⁻¹): total N, 1; total P, 1 (NaHCO₃-extractable P);
15 total K, 11. The soil texture comprised 38.3% sand, 47.1% silt and 14.6% clay.

16 Four RILs from the above-described P population were selected in previous
17 assays for this study under drought stress conditions, on the basis of their good
18 levels of root colonization by the AM fungus *R. irregularis* and the PGPR *V.*
19 *paradoxus*, as well as, positive growth responses. Seeds from the different lines and
20 the commercial cultivar (Boludo) were pre-germinated on sand for ten days and then
21 transferred to 1.5 L plastic pots filled with 1200 g of the soil/sand mixture described
22 above.

23 Mycorrhizal inoculum was provided by INOQ GmbH (<http://inoq.de/>) and
24 consisted of sand containing spores, mycelia and AM fungi-colonized root fragments.
25 The density of inoculum was estimated to 220000 propagules L⁻¹. Approximately 40

1 mL (circa 80 g) of the AM inoculum were applied to the appropriate pots, following
2 manufacturer's recommendations. Plants that were not inoculated with the AM
3 fungus, received the same amount of sand together with a 3 mL aliquot of a filtrate
4 (<20 µm) of the AM inoculum to provide a general microbial population free of AM
5 propagules.

6 The *Variovorax paradoxus* 5C-2 inoculum was also provided by INOQ GmbH
7 in liquid medium (10^8 cfu/mL), so that 1.5 mL of the purified bacterial culture was
8 diluted with sterile water in a final volume of 15 mL and applied to the appropriate
9 pots, according to manufacturer's recommendations. Thus, each pot received
10 1.5×10^8 cfu.

11

12 2.3. Growth conditions

13 The experiment was carried out under greenhouse conditions with
14 temperatures ranging from 19 to 25°C, 16/8 h light/dark period, a relative humidity of
15 50-60% and an average photosynthetic photon flux density of $800 \mu\text{mol m}^{-2} \text{s}^{-1}$, as
16 measured with a light meter (LICOR, Lincoln, NE, USA, model LI-188B).

17 Plants were cultivated for 9 weeks. After week 3, plants received weekly 15
18 mL per pot of Hoagland's nutrient solution (Hoagland and Arnon, 1950) containing
19 only 25% of P, to prevent inhibition of AM root colonization. The plants were
20 cultivated under well-watered conditions for 5 weeks. At that point, half of the pots
21 per each of the inoculation treatments were left well-watered, and the other half
22 subjected to drought stress for additional four weeks before harvest.

23 Soil moisture was controlled with the ML2 ThetaProbe (AT Delta-T Devices
24 Ltd., Cambridge, UK). Water was supplied daily to maintain soil at 100% of field
25 capacity (corresponding to 22% volumetric soil moisture measured with the

1 ThetaProbe, as determined experimentally in a previous experiment using a pressure
2 plate apparatus) during the first 5 weeks after sowing. Then half of the plants were
3 allowed to dry until soil water content reached 60% of field capacity (two days
4 needed), while the other half were maintained at field capacity. This soil water
5 holding capacity corresponds to 9% volumetric soil moisture measured with the
6 ThetaProbe (also determined experimentally with a pressure plate apparatus in a
7 previous assay). **The level of drought stress (60% of field capacity) was selected on**
8 **the basis of previous studies in order to subject tomato to a sharp drought stress**
9 **(Ruiz-Lozano et al. 2016).** The soil water content was measured daily with the
10 ThetaProbe ML2 before rewatering (at the end of the afternoon), reaching a minimum
11 soil water content around 55% of field capacity. The amount of water lost was added
12 to each pot to keep the soil water content at the desired level (Porcel and Ruiz-
13 Lozano, 2004). Plants were maintained under such conditions for 4 additional weeks
14 before harvesting.

15

16 *2.4. Parameters measured*

17 *2.4.1. Biomass production and symbiotic development*

18 **The shoot dry weight (SDW) was measured as an integrative index of plant**
19 **performance under the growing conditions assayed.** At harvest time (9 weeks after
20 transplanting), shoots were de-topped from roots, and fresh weights recorded.
21 Samples were kept to measure dry weight after drying in a forced hot-air oven at 70
22 °C for two days.

23 The percentage of mycorrhizal root colonization was estimated in five roots
24 per RIL line and treatment combination. Approximately 0.5 g of root tissues were
25 cleared in 10% KOH and stained with 0.05% trypan blue in lactic acid (v/v). The

1 extent of mycorrhizal colonization was calculated according to the gridline intersect
2 method (Giovannetti and Mosse, 1980).

3 To quantify bacterial root colonization as previously described (Belimov et al.,
4 2015), fresh tomato root samples were weighed and homogenized in sterile tap water
5 with a sterile mortar and pestle. Homogenates were serially diluted in 10-fold steps
6 and 20 μL aliquots were plated in three replicates on LB agar supplemented with 30
7 $\mu\text{g mL}^{-1}$ kanamycin and 20 $\mu\text{g mL}^{-1}$ rifampicin, to which *V. paradoxus* 5C-2 naturally
8 shows resistance, and 40 $\mu\text{g mL}^{-1}$ nystatin to prevent fungal growth. The
9 characteristic colonies of *V. paradoxus* 5C-2 were counted after incubation at 28 °C
10 for 3 days.

11

12 *2.4.2. Plant CO₂ assimilation rate and leaf chlorophyll content*

13 The CO₂ assimilation rate was measured 2 h after sunrise on the second
14 youngest leaf from each plant. We used a portable infrared gas analyzer LI-6400 (LI-
15 COR Biosciences, Inc., Lincoln, NE, USA), which allows environmental conditions
16 inside the chamber to be precisely controlled, with 400 ppm CO₂ concentration, a
17 humidity of 50% and a light intensity of 1000 $\mu\text{E m}^{-2} \text{s}^{-1}$. The photosynthetic
18 parameters were calculated by using LI-6400 6.1 software.

19 Leaf chlorophyll contents were estimated 4 hours after sunrise using a SPAD,
20 model 502 (Minolta, [München, Germany](#)) on the second youngest leaf for each plant.

21

22 *2.4.3. Oxidative damage to lipids and proline content*

23 Oxidative damage to lipids was measured by grinding 500 mg of fresh leaf
24 tissues with an ice-cold mortar and 6 ml of 100 mM potassium phosphate buffer (pH
25 7). Homogenates were filtered through one Miracloth layer and centrifuged at 15,000

1 g for 20 min. The chromogen was formed by mixing 200 mL of supernatants with 1
2 mL of a reaction mixture containing 15% (w/v) trichloroacetic acid (TCA), 0.375%
3 (w/v) 2-thiobarbituric acid (TBA), 0.1% (w/v) butyl hydroxytoluene, 0.25 N HCl and by
4 incubating the mixture at 100 °C for 30 min. After cooling at room temperature, tubes
5 were centrifuged at 800 g for 5 min and absorbance of the supernatant was
6 measured at 532 nm. Lipid peroxidation was estimated as the content of 2-
7 thiobarbituric acid-reactive substances (TBARS) and expressed as equivalents of
8 malondialdehyde (MDA). The calibration curve was made using MDA in the range of
9 0.1-10 nmol. A blank for all samples was prepared by replacing the sample with
10 extraction medium, and controls for each sample were prepared by replacing TBA
11 with 0.25 N HCl. In all cases, 0.1% (w/v) butyl hydroxytoluene was included in the
12 reaction mixtures to prevent artefactual formation of 2-thiobarbituric acid-reactive
13 substances (TBARS) during the acid-heating step of the assay.

14 Free proline was extracted from 1 g fresh tissues in sulfosalicylic acid 5% (w/v).
15 Proline was estimated by spectrophotometric analysis at 515 nm of the ninhydrin
16 reaction, according to Bates et al. (1973).

17

18 *2.4.4. Root hydraulic conductivity*

19 Root hydraulic conductance (K_r) was measured with a high pressure flow
20 meter (HPFM Dynamax Inc., Houston). K_r measurements utilized the transient mode,
21 where the pressure increases over a range and K_r is calculated from the slope of flow
22 versus pressure. For that, detached tomato roots were connected to the HPFM using
23 compression couplings, and water was perfused at increasing pressures ranging
24 from 0 to 500 kPa. Root volume was calculated after the measurements as in Calvo-

1 Polanco et al. (2012) and hydrostatic root hydraulic conductivity (L_{pr}) determined by
2 dividing K_r by the root volume.

3

4 *2.4.5 PIP aquaporins abundance and phosphorylation status*

5 We analyzed PIP1 and PIP2 proteins abundance and the PIP2
6 phosphorylation state in root samples. We checked accumulation of these proteins
7 since aquaporin gene expression is not always correlated with protein abundance,
8 and aquaporin activity can be regulated by phosphorylation events (Prado et al.,
9 2013). The phosphorylation of PIP2 aquaporins was quantified by the use of two
10 different antibodies that recognize a phosphorylated Serine residue at position 280
11 (PIP2₂₈₀) or two phosphorylated Serine residues at positions 280 and 283 (PIP2<sub>280-
12 283</sub>) in the C-terminal end (Calvo-Polanco et al., 2014a,b). It has been previously
13 shown that the phosphorylation of PIP2 aquaporins at Ser280 and Ser283 was linked
14 to the regulation of hydraulic conductivity in plants (Prado et al., 2013).

15 Microsomes were isolate from three different tomato roots per RIL and
16 treatment combination, as described in Hachez et al. (2006). Two micrograms of the
17 protein extracts were used for ELISA analyses to determine the abundance of the
18 different tomato proteins, as described in Calvo-Polanco et al. (2014a,b). We used
19 four different primary antibodies (at a dilution of 1:1000), two antibodies that
20 recognize several PIP1s and PIP2s, and two antibodies that recognize the
21 phosphorylation of PIP2 proteins in the serine residue at the C-terminal end, Ser280
22 (PIP2₂₈₀) or in two serine residues at the C-terminal end (Ser 280 and Ser 283 -
23 PIP2_{280/283}) (Prado et al., 2013; Calvo-Polanco et al., 2014a,b). All antibodies were
24 designed against the most conservative regions of these aquaporin groups. To detect
25 PIP1 aquaporins, we used the first 26 amino acids of the N-terminal part of the

1 PvPIP1;3 protein (accession No. DQ855475). To detect PIP2 aquaporins, we used
2 the last 12 amino acids of the C-terminal part of the PvPIP2;1 protein (accession No.
3 AY995195). To detect phosphorylated PIP2, we used the same protein PvPIP2;1 as
4 the amino acid sequence but with one or two serine groups phosphorylated,
5 AIKALG{pSER}FR{pSER}NA (Abyntek Biofarma SL, BiotechSpain), as described by
6 Calvo-Polanco et al (2014b). A goat anti-rat IgG coupled to horseradish peroxidase
7 (Sigma-Aldrich Co., USA) was used as secondary antibody at 1:10,000 for PIP1.
8 Goat anti-rabbit IgG coupled to horseradish peroxidase (Sigma-Aldrich Co., USA)
9 was used as secondary antibody at 1:10,000 for PIP2 and PIP2₂₈₀, and PIP2_{280/283}.
10 Protein quantification was carried out in three different independent root samples per
11 treatment (n=3), replicated three times each. The specificity of the PIP2 and
12 phosphorylated antibodies PIP2₂₈₀, and PIP2_{280/283} is described in Calvo-Polanco et
13 al. (2014b). The equal loading of proteins in the different treatments was confirmed
14 by staining a gel blot loaded with the same quantities used for the ELISA
15 measurement with Coomassie brilliant blue and also by Bradford quantification
16 (Bradford, 1976).

17

18 *2.5. Statistical Analysis*

19 Within each recombinant inbred line, data were subjected to analysis of
20 variance (ANOVA) with the Proc MIXED procedure in SAS (version 9.2, SAS institute
21 Inc., NC, USA) together with the post-hoc Tukey's test to detect significant
22 differences among treatment means. The different inoculation treatments and water
23 regimes were the sources of variation (Table 1S).

24

25

1 **3. Results**

2

3 *3.1. Microbial root colonization*

4 The percentage of root length colonized by the AM fungus ranged from 26% in
5 RIL100 to 67% in RIL66 when co-inoculated with the PGPR bacterium (Figure 1S A).
6 The commercial line Boludo, also exhibited high mycorrhizal root colonization,
7 reaching 62% of root length colonized. However, the co-inoculation of Boludo plants
8 with the PGPR decreased the AM root colonization as compared to plants inoculated
9 with the AM fungus alone. In RILs 66 and 100, the co-inoculation of the PGPR had a
10 positive effect on AM root colonization under well-watered conditions. No AM root
11 colonization was observed in uninoculated plants.

12 The bacterial colonization of inoculated tomato roots in the different RILs was
13 estimated as the number of colony-forming units (CFU) g⁻¹ root fresh weigh (RFW)
14 and ranged from 5×10⁵ CFU g⁻¹ RFW in RIL20 to 30×10⁷ CFU g⁻¹ RFW in cv. Boludo,
15 with most plants having an average of 6×10⁶ CFU g⁻¹ RFW (Figure 1S B). No
16 colonies were recovered from non-inoculated plants.

17

18 *3.2. Plant biomass*

19 The inoculation of the different tomato lines had different effects on SDW
20 according to the genotype studied (Figure 1). Under well-watered conditions, the
21 different inoculation treatments did not affect the SDW of Boludo and RIL40 plants
22 (Figure 1). However, the AM fungus and AM fungus+PGPR treatments increased the
23 SDW of RIL66 plants and decreased the SDW of RIL20 and RIL100 plants (Figure 1).

24 After 4 weeks of drought treatment, there was a general reduction of SDW in
25 Boludo and RIL20 plants, with no significant differences between the various

1 inoculation treatments and the uninoculated control plants. Drought decreased SDW
2 of RIL66 plants by 79%, but plants treated with the different microbial inoculants had
3 significantly higher SDW than the control plants, with the maximum values in the AM
4 and AM fungus+PGPR treatments (Figure 1). Therefore, RIL66 clearly obtained
5 beneficial effects from PGPR and AM inoculation under drought conditions. In RIL40,
6 drought stress and PGPR treatment reduced SDW by 71% and 75%, respectively,
7 while the presence of AM fungus recovered the SDW values as in well-watered
8 control plants (Figure 1). A negative effect was observed for RIL20 only under well-
9 watered conditions.

10

11 3.3. *Plant CO₂ assimilation rate and leaf chlorophyll content*

12 Drought stress considerably decreased CO₂-assimilation rate in most of the
13 RILs (Figure 2A), but this effect was counteracted in some RILs. Thus, inoculating
14 RIL20 with the AM fungus enhanced the CO₂-assimilation rate under drought stress.
15 **Plants from RIL40 exhibited a similar CO₂-assimilation rate under drought stress**
16 **conditions, regardless of the microbial treatment. The PGPR inoculation enhanced**
17 **this parameter only under well-watered conditions.** In plants from RIL66, both the AM
18 fungus and the AM fungus+PGPR treatments maintained a high CO₂-assimilation
19 rate, which was similar to that under well-watered conditions. Plants from RIL100
20 exhibited similar CO₂-assimilation rate under well-watered and under drought stress
21 conditions, regardless of the microbial treatment, but this rate was lower than in the
22 other RILs.

23 Leaf chlorophyll content increased under drought stress treatment in Boludo
24 and RIL20 plants, with no significant changes as compared to control plants in RIL40,
25 RIL66 and RIL100 (Figure 2B). In any case, under drought stress, there was little

1 effect of the different inoculation treatments, except for the increase in leaf
2 chlorophyll content in the AM plants from RIL40 and RIL66 (Figure 2B).

3

4 *3.4. Shoot oxidative damage to lipids and proline content*

5 Oxidative damage to lipids was considerably enhanced by drought stress in
6 Boludo plants, in plants from RIL20 inoculated with the PGPR and in those from
7 RIL100 (Figure 3A). However, plants from RIL40 and RIL66 exhibited the lowest
8 values of oxidative damage either under well-watered or under drought stress
9 conditions. No protective effect by the microbial inoculants was observed on this
10 parameter at any of the RILs assayed.

11 Drought stress induced a general increase of shoot proline content in the
12 entire RILs studied (Figure 3B). Under drought stress conditions, Boludo plants
13 accumulated higher amounts of proline but it was significantly reduced by the
14 different inoculation treatments (Figure 3B). The same trend was observed in RIL66
15 plants, where PGPR and AM fungus treatments (alone or in combination) halved
16 proline content. In RIL20 and RIL40, only the dual inoculation of PGPR plus AM
17 fungus decreased proline accumulation under drought stress.

18

19 *3.5. Root hydraulic conductivity*

20 The root hydraulic conductivity (L_{p_r}) of plants that were cultivated under well-
21 watered conditions showed little variation between RILs and microbial treatments
22 (Figure 4). Under drought stress, the inoculation with the PGPR, the AM fungus or
23 combination of both microorganisms decreased L_{p_r} in Boludo plants, **as compared to**
24 **the uninoculated control**. In RIL20 only the inoculation with the PGPR alone
25 enhanced L_{p_r} under drought stress conditions, **as compared to the uninoculated**

1 **control**. In contrast, the dual inoculation of the PGPR plus the AM fungus decreased
2 this parameter to values similar to uninoculated control plants. In plants from RIL40,
3 Lp_r was enhanced only by the inoculation with the AM fungus alone. In RIL66, Lp_r
4 was enhanced **over uninoculated control** when plants were inoculated with the AM
5 fungus in combination with the PGPR, reaching the highest values of Lp_r under such
6 conditions. In contrast, microbial treatments did not affect Lp_r of RIL100 plants.

7

8 *3.6. Accumulation of PIPs in roots of tomato plants*

9 Abundance of PIP1 aquaporins proteins in the Boludo cultivar was little
10 affected by the microbial treatments or the watering conditions (Figure 5A). Only a
11 slight decrease was observed in AM plants, both under well-watered or under
12 drought stress conditions. In RIL20 and RIL40 the accumulation of PIP1s was
13 significantly enhanced by drought stress, mainly in uninoculated control plants.
14 However, under drought stress, the accumulation of these proteins decreased after
15 inoculation with either the PGPR or the AM fungus. In RIL66 and RIL100, the trend
16 was different since PIP1s accumulated more in plants that were inoculated with the
17 PGPR or the AM fungus and subjected to drought stress.

18 The abundance of non-phosphorylated PIP2s proteins in Boludo cultivar was
19 also little affected by the microbial or watering treatments (Figure 5B). Again, only a
20 decrease in the abundance of these proteins was observed in AM plants, both under
21 well-watered or under drought stress conditions. In RIL20 the presence of PIP2s was
22 induced by drought stress only in plants inoculated with the PGPR. However, in AM
23 plants (alone or in combination with the PGPR) these proteins were less abundant. **In**
24 **uninoculated** RIL40 and RIL66 **plants**, the accumulation of PIP2s was enhanced by
25 drought. However, in RIL40 the inoculation of the PGPR further enhanced the

1 abundance of PIP2s, while in RIL66 it reduced the accumulation as compared to
2 droughted uninoculated plants. In both RILs the inoculation with the AM fungus
3 avoided the drought-induced accumulation of these aquaporins. In RIL100 there was
4 almost no effect of the microbial or the watering treatments on the accumulation of
5 non-phosphorylated PIP2s (Figure 5B).

6 In the case of phosphorylated PIP2s, the patterns of protein accumulation
7 were similar for both kinds of antibodies used (Figures 6A and 6B). Thus, drought
8 stress induced the accumulation of phosphorylated PIP2s in uninoculated control
9 plants or in plants singly inoculated with the PGPR in RILs 20, 40 and 66. Such an
10 effect was not observed in plants from Boludo cultivar and was not consistent in
11 plants from RIL100. A common effect was observed in plants from all lines. Indeed,
12 drought-induced accumulation of phosphorylated PIP2s was avoided when plants
13 were inoculated with the AM fungus, either alone or in combination with the PGPR.
14 Furthermore, these treatments exhibited lower abundance of phosphorylated PIP2s
15 than uninoculated control plants. This reduction of protein abundance in AM roots
16 was observed in most RILs even under well-watered conditions and was particularly
17 evident in RIL66.

18

19 **4. Discussion**

20 The reduction in plant biomass production caused by drought stress has been
21 linked to direct effects on the plant photosynthetic capacity due to reduced stomatal
22 conductance. This, in turn, results in low CO₂ supply to Rubisco. Thus, maintaining a
23 high stomatal conductance allows the plant a higher CO₂ uptake for photosynthesis
24 (Davies et al., 1993; Sheng et al., 2008).

1 Although inoculating tomato plants with the AM fungus *R. irregularis* MUCL
2 41833 or the PGPR *V. paradoxus* 5C-2 resulted in high root colonization rates in the
3 different RILs considered, the responses of these RILs to the presence of the AM
4 fungus and the PGPR (alone or in combination) varied considerably. One of the main
5 benefits of AM or AM + PGPR inoculation for RIL66 plants under drought stress
6 conditions was the maintenance of high photosynthetic rates as compared to non-
7 inoculated plants. Increased photosynthetic activity or water use efficiency have been
8 reported in AM plants growing under drought stress (Birhane et al., 2012; Liu et al.,
9 2015), which was attributed to mycorrhizal enhancement of plant water status, rather
10 than to a direct influence on the efficiency of photosystem II (Sheng et al., 2008).
11 However, in salinized tomato and rice plants, mycorrhization improved photosynthetic
12 activity by both elevating stomatal conductance and protecting PSII photochemical
13 processes (Hajiboland et al., 2010; Porcel et al., 2015). Stomatal changes in AM
14 plants have been linked to altered plant hormone status (Augé, 2000) or to a higher
15 capacity for CO₂ fixation. Indeed, mycorrhizal grapevines showed higher Rubisco
16 activity than non-AM ones during drought episodes (Valentine et al. 2006), as did
17 salinized rice plants (Porcel et al., 2015).

18 Drought decreases both soil water potential and the soil-root gradient of water
19 potential favouring root water uptake, thereby reducing the water flow toward roots.
20 To counter this effect, many plants increase their osmotic potential by synthesizing
21 and accumulating compatible osmolytes such as proline, to maintain root water
22 uptake (Porcel and Ruiz-Lozano, 2004; Flowers and Colmer, 2008). Under drought
23 stress, proline accumulation was higher in most of the RILs, but this accumulation
24 was reduced by the presence of microorganisms, especially in RIL66 plants. This
25 suggests that AM- and PGPR-inoculated plants were less strained by the drought

1 stress applied, due to other drought-avoidance mechanisms such as water uptake by
2 fungal hyphae or hormonal-mediated regulation of stomatal conductance, and that
3 they had a lower need for osmotic adjustment. While non-AM lettuce plants
4 accumulated more proline in their shoots than AM plants under drought, AM plants
5 accumulated more proline in the roots than non-AM plants (Ruíz-Lozano et al., 2011).
6 Thus, in root tissues, AM plants accumulate more proline in order to cope with the
7 low water potential of drying soil and to keep a water potential gradient favourable to
8 water entrance into the roots, as was also found in soybean (Porcel and Ruíz-Lozano,
9 2004). Proline homeostasis may be important to sustain growth under long-term
10 stress, since proline accumulated during a stress episode can be degraded to
11 provide a supply of energy to drive growth once the stress is relieved (Kishor and
12 Sreenivasulu, 2014).

13 The differences in proline accumulation among RILs and microbial treatments
14 may also be related to hormonal changes in these plants or due to the microbial
15 treatments. ABA, auxins and salicylic acid are known to up-regulate proline synthesis,
16 while cytokinin down-regulates proline accumulation (Kishor and Sreenivasulu, 2014).

17 Drought stress generates a secondary oxidative stress in plant tissues due to
18 the accumulation of ROS. Cytotoxic ROS can destroy normal metabolism through
19 oxidative damage of lipids, proteins and nucleic acids (Miller et al., 2010; Noctor et al.,
20 2014). In the present study drought significantly increased the level of oxidative
21 damage to lipids, which was accentuated when cv. Boludo received the AM and
22 AM+PGPR treatments. Generally, the RILs showed lower levels of drought-induced
23 oxidative damage, except in RIL100. Generally, the microbial treatments applied did
24 not alter the rates of oxidative damage in the RILs. The differences observed are only
25 due to the own RIL used. Thus, RIL66 must have additional mechanisms to respond

1 to the drought-induced oxidative stress as compared to Boludo, which seems quite
2 sensible. It is known that ROS accumulation depends on the balance between its
3 production and its elimination (Miller et al., 2010; Scheibe and Beck, 2011). Thus, the
4 ROS scavenging systems may be more effective in plants from RIL40 or RIL66 than
5 in those from RIL100 or the Boludo cultivar.

6 A fine control of water transport is of key importance for plant survival under
7 drought stress conditions, as it decreases L_p_r (Aroca et al., 2012), a process in which
8 PIPs play a fundamental role (Maurel et al. 2015). In addition, AM fungi can affect the
9 L_p_r of host plants through regulation of plant aquaporins (Bárzana et al., 2014; Calvo-
10 Polanco et al., 2014a; Sánchez-Romera et al., 2016), being this effect considered as
11 an important factor in the regulation of water relations in mycorrhizal plants (Lee et al.,
12 2010; Ruiz-Lozano et al., 2012). PIP2s are usually considered as the main
13 aquaporins responsible for the major water transport capacity in plants (Chaumont et
14 al., 2000). However, PIP1 aquaporins have also been shown to play a role in water
15 transport in plants (Zou et al., 2010) in combination with PIP2 proteins via
16 heteromerization (Zelazny et al., 2007; Li et al., 2013), and in the trafficking of PIP
17 proteins to the plasma membrane (Zelazny et al., 2007; Hachez et al., 2013).

18 Generally, the microbial treatments did not alter L_p_r under well-watered
19 conditions, but more pronounced effects were seen in droughted plants. Taking
20 RIL20 and RIL66 as lines with contrasting responses to the microbial inoculants it is
21 evident that L_p_r was unaltered by microbial treatments under well-watered conditions.
22 In contrast, under drought stress conditions, plants from RIL20 and RIL66 also
23 exhibited contrasting effects of the microbial inoculants on L_p_r . Indeed, plants from
24 RIL20 enhanced the L_p_r only when inoculated with the PGPR alone, but the dual
25 inoculation with the AM fungus avoided this increase (Figure 4). In contrast, in RIL66,

1 the highest L_{p_r} values were achieved under drought stress conditions in plants dually
2 inoculated with the PGPR and the AM fungus. Inhibiting root ethylene production
3 reversed the limiting effect of P-deprivation on L_{p_r} (Li et al., 2009) and it is plausible
4 that the impact of the ACC-deaminase containing PGPR in decreasing root ethylene
5 production (Belimov et al., 2015) enhanced L_{p_r} . Why this effect should occur only in
6 RIL20 is not clear, although PGPR root colonization under drought was lowest in this
7 line, and physiological impacts of ACC-deaminase containing PGPR can be dose-
8 dependent (Belimov et al., 2007).

9 The correlation between the measured L_{p_r} values and PIP accumulation
10 patterns was not evident for most of the RILs analyzed, as previously observed
11 (Boursiac et al., 2005; Aroca et al., 2007; Ruiz-Lozano et al., 2009). This is not
12 surprising since symplastic movement of water via plasmodesmata may also
13 contribute significantly to hydraulic conductivity (Galmés et al., 2007), and aquaporin
14 regulation occurs at both transcriptional and post-transcriptional levels (Zelazny et al.,
15 2007).

16 In any case, in RIL20 L_{p_r} showed a significant statistical correlation with the
17 accumulation of PIP1s, non-phosphorylated PIP2s and both phosphorylated PIP2s
18 (Table 1). Thus, in RIL20 the variation in L_{p_r} by the PGPR and the AM fungus under
19 drought stress seems to be directly related to the regulation of PIPs aquaporins
20 (Chaumont and Tyerman, 2014). Conversely, in RIL66 L_{p_r} followed a significant
21 negative correlation with accumulation of non-phosphorylated PIP2s and both
22 phosphorylated PIP2s (Table 1). This suggests that in RIL66 the enhanced root
23 hydraulic conductivity of plants inoculated with the PGPR and the AM fungus was
24 rather related to altered apoplastic water flow in these plants. It must be taken into
25 account that the values of L_{p_r} measured in this study includes both apoplastic and

1 symplastic water flow. In this regards, the presence of mycorrhizal fungi within the
2 roots may have greatly contributed to the increase of the apoplastic water flow within
3 the roots as previously reported (Lehto and Zwiazek, 2011; Barzana et al., 2012).
4 Increased water uptake by mycorrhizal plants under drought has been related to the
5 increased absorbing surface of growing hyphae, and mycorrhizal ability to take up
6 water from soil pores inaccessible to roots, as AM hyphae represent a low-resistance
7 way for water movement until root cells (Ruiz-Lozano, 2003; Allen, 2009; Lehto and
8 Zwiazek, 2011). Thus, water movement through AM fungal hyphae under such
9 conditions can be critical to improve the water supply to the plant and, therefore, cell-
10 to-cell and apoplastic pathways increase (Barzana et al., 2012). On the other hand,
11 AM fungal aquaporins have been related to water transport in the extraradical
12 mycelium and in the periarbuscular membrane (Li et al., 2013). Thus, in AM plants,
13 the enhanced root hydraulic conductivity could be also due to the activity of the own
14 fungal aquaporins (Bárzana et al., 2014; 2015).

15

16 **5. Conclusions**

17 Results obtained clearly demonstrate a variation in the performance of the
18 different tomato RILs under conditions of drought stress, as well as, a differential
19 effect of the microbial inoculants (AM fungus and/or PGPR) on plant performance,
20 depending on the RIL involved. Thus, RIL66 is the one obtaining the maximum
21 benefit from inoculation with the AM fungus and the PGPR. In contrast, RIL20 or
22 RIL100 received little benefit from the microorganisms applied under conditions of
23 drought stress. This genetic diversity in microbial response may be exploited
24 commercially, particularly if a selected RIL is used as stress-tolerant rootstock.

1 We propose that RIL66 could be selected as a good plant material to be used
2 as rootstock in a grafting program to improve tomato growth and productivity under
3 water limiting conditions. Since RIL66 is highly responsive to microbial inoculants,
4 this grafting strategy should be combined with inoculation of the AM fungus *R.*
5 *irregularis* MUCL41833 and the PGPR *V. paradoxus* 5C-2 in order to improve plant
6 productivity while reducing water and fertilizer inputs under conditions of drought
7 stress.

8

9 **Acknowledgements**

10 This research has received funding from the European Union's Seventh
11 Framework Programme for research, technological development and demonstration
12 under grant agreement no 289365 (ROOTOPOWER project). We thank Eva Lucic
13 (INOQ GmbH) for providing the AM and PGPR inocula, and Aquilino Sánchez
14 (UNIGENIA Bioscience) for providing seeds from the different RILs used.

15

16 **References**

17 Albacete, A., Martínez-Andújar, C., Dodd, I.C., Giuffrida, F., Hichri, I., Lutts, S.,
18 Thompson, A., Asins, M.J., 2015a. Rootstock-mediated variation in tomato
19 vegetative growth under drought, salinity and soil impedance stresses. *Acta Hortic.*
20 1086, 141-146.

21 Albacete, A., Martínez-Andújar, C., Martínez-Pérez, A., Thompson, A.J., Dodd, I.C.,
22 Pérez-Alfocea, F., 2015b. Unravelling rootstock×scion interactions to improve food
23 security. *J. Exp. Bot.* 66, 2211-2226.

1 Albacete, A., Martínez-Andújar, C., Pérez-Alfocea, F., Ruiz-Lozano, J.M., Asins, M.J.,
2 2015c. Rootstock-mediated variation in tomato vegetative growth under low
3 potassium or phosphorous supplies. *Acta Hortic.* 1086, 147-152.

4 Allen, MF., 2009. Bidirectional water flows through the soil-fungal-plant mycorrhizal
5 continuum. *New Phytol.* 182, 290-293.

6 Aroca, R., Porcel, R., Ruiz-Lozano, J.M., 2007. How does arbuscular mycorrhizal
7 symbiosis regulate root hydraulic properties and plasma membrane aquaporins in
8 *Phaseolus vulgaris* under drought, cold or salinity stresses? *New Phytol.* 173, 808-
9 816.

10 Aroca, R., Porcel, R., Ruiz-Lozano, J.M., 2012. Regulation of root water uptake
11 under abiotic stress conditions. *J. Exp. Bot.* 63, 43-57.

12 Asins, M.J., Bolarín, M.C., Pérez-Alfocea, F., Estañ, M.T., Martínez-Andújar, C.,
13 Albacete, A., Villalta, I., Bernet, G.P., Dodd, I.C., Carbonell, E.A., 2010. Genetic
14 analysis of physiological components of salt tolerance conferred by *Solanum*
15 rootstocks. What is the rootstock doing for the scion? *Theor. Appl. Genet.* 121,
16 105-115.

17 Asins, M.J., Raga, V., Roca, D., Belver, A., Carbonell, E.A., 2015. Genetic dissection
18 of tomato rootstock effects on scion traits under moderate salinity. *Theor. Appl.*
19 *Genet.* 128, 667-679.

20 Augé, RM., 2000. Stomatal behavior of arbuscular mycorrhizal plants, in: Kapulnik, Y.,
21 Douds, D.D. (Eds.), *Arbuscular Mycorrhizas: Physiology and Function*. Kluwer
22 Academic Publishers, Dordrecht, the Netherlands. pp. 201-237.

23 Azcón, R., Medina, A., Aroca, R., Ruiz-Lozano, J.M., 2013. Abiotic stress
24 remediation by the arbuscular mycorrhizal symbiosis and rhizosphere

1 bacteria/yeast interactions, in: de Bruijn F.J. (Ed.) Molecular Microbial Ecology of
2 the Rhizosphere, John Wiley and Sons Ltd, England, pp. 991-1002.

3 Bárzana, G., Aroca, R., Bienert, P., Chaumont, F., Ruiz-Lozano, J.M., 2014. New
4 insights into the regulation of aquaporins by the arbuscular mycorrhizal symbiosis
5 in maize plants under drought stress and possible implications for plant
6 performance. *Mol. Plant-Microbe Interact.* 27, 349-363.

7 Bárzana, G., Aroca, R., Paz, J.A., Chaumont, F., Martínez-Ballesta, M.C., Carvajal,
8 M., Ruiz-Lozano, J.M., 2012. Arbuscular mycorrhizal symbiosis increases relative
9 apoplastic water flow in roots of the host plant under both well-watered and
10 drought stress conditions. *Ann. Bot.* 109, 1009-1017.

11 Bárzana, G., Aroca, R., Ruiz-Lozano, J.M., 2015. Localized and non-localized effects
12 of arbuscular mycorrhizal symbiosis on accumulation of osmolytes and aquaporins
13 and on antioxidant systems in maize plants subjected to total or partial root drying.
14 *Plant, Cell Environ.* 38, 1613-1627.

15 Bates, L.S., Waldren, R.P., Teare, I.D., 1973. Rapid determination of free proline for
16 water stress studies. *Plant Soil* 39, 205-207.

17 Belimov, A.A., Dodd, I.C., Safronova, V.I., Hontzeas, N., Davies, W.J., 2007.
18 *Pseudomonas brassicacearum* strain Am3 containing 1-aminocyclopropane-1-
19 carboxylate deaminase can show both pathogenic and growth-promoting
20 properties in its interaction with tomato. *J. Exp. Bot.* 58, 1485-1495.

21 Belimov, A.A., Dodd, I.C., Safronova, V.I., Shaposhnikov, A.I., Azarova, T.S.,
22 Makarova, N.M., Davies, W.J., Tikhonovich, I.A., 2015. Rhizobacteria that produce
23 auxins and contain ACC deaminase decrease amino acid concentrations in the
24 rhizosphere and improve growth and yield of well-watered and water-limited potato
25 (*Solanum tuberosum*). *Ann. Appl. Biol.* 167, 11-25.

- 1 Bheemareddy, V.S., Lakshman, H.C., 2011. Effect of AM fungus *Glomus*
2 *fasciculatum* on metabolite accumulation in four varieties of *Triticum aestivum* L.
3 under short-term water stress. *Vegetos* 24, 41-49.
- 4 Birhane, E., Sterck, F.J., Fetene, M., Bongers, F., Kuyper, T.W., 2012. Arbuscular
5 mycorrhizal fungi enhance photosynthesis, water use efficiency, and growth of
6 frankincense seedlings under pulsed water availability conditions. *Oecologia* 169,
7 895-904.
- 8 Boursiac, Y., Chen, S., Luu, D-T., Sorieul, M., Dries, N., Maurel, C., 2005. Early
9 effects of salinity on water transport in *Arabidopsis* roots. Molecular and cellular
10 features of aquaporin expression. *Plant Physiol.* 139, 790-805.
- 11 **Bradford, M.M., 1976. A rapid and sensitive method for the quantitation of microgram**
12 **quantities of protein utilizing the principle of protein-dye binding. *Anal Biochem.* 72,**
13 **248-254.**
- 14 Calvo-Polanco, M., Molina, S., Zamarreno, A.M., Garcia-Mina, J.M., Aroca, R., 2014a.
15 The symbiosis with the arbuscular mycorrhizal fungus *Rhizophagus irregularis*
16 drives root water transport in flooded tomato plants. *Plant Cell Physiol.* 55, 1017-
17 1029.
- 18 Calvo-Polanco, M., Sánchez-Romera, B., Aroca, R., 2014b. Mild salt stress
19 conditions induce different responses in root hydraulic conductivity of *Phaseolus*
20 *vulgaris* over-time. *PLoS One* 9, e90631.
- 21 Calvo-Polanco, M., Señorans, J., Zwiazek, J.J., 2012. Role of adventitious roots in
22 water relations of tamarack (*Larix laricina*) seedlings exposed to flooding. *BMC*
23 *Plant Biol.* 12, 99.
- 24 Cabot, C., Sibole, J.V., Barceló, J., Poschernreider, C., 2014. Lesson from crop
25 plants struggling with salinity. *Plant Sci.* 226, 2-13.

- 1 Chaumont, F., Barrieu, F., Jung, R., Chrispeels, M.J., 2000. Plasma membrane
2 intrinsic proteins from maize cluster in two sequence subgroups with differential
3 aquaporin activity. *Plant Physiol.* 122, 1025-1034.
- 4 Chaumont, F., Tyerman, S.D., 2014. Aquaporins: highly regulated channels
5 controlling plant water relations. *Plant Physiol.* 164, 1600-1618.
- 6 Davies, F.T., Potter, J.R., Linderman, R.G., 1993. Drought resistance of mycorrhizal
7 pepper plants independent of leaf P-concentration—response in gas exchange and
8 water relations. *Physiol. Plant.* 87, 45-53.
- 9 Dobra, J., Motyka, V., Dobrev, P., Malbeck, J., Prasil, I.T., Haisel, D., Gaudinova, A.,
10 Havlova, M., Gubis, J., Vankova, R., 2010. Comparison of hormonal responses to
11 heat, drought and combined stress in tobacco plants with elevated proline
12 contents. *J. Plant Physiol.* 167, 1360-1370.
- 13 Dodd, I.C., Ruiz-Lozano, J.M., 2012. Microbial enhancement of crop resource use
14 efficiency. *Curr. Opin. Biotechnol.* 23, 236-242.
- 15 Flowers, T.J., Colmer, T.D., 2008. Salinity tolerance in halophytes. *New Phytol.* 179,
16 945-963.
- 17 Galmés, J., Medrano, H., Flexas, J., 2007. Photosynthetic limitations in response to
18 water stress and recovery in Mediterranean plants with different growth forms.
19 *New Phytol.* 175, 81-93.
- 20 Gill, S.S., Tuteja, N., 2010. Reactive oxygen species and antioxidant machinery in
21 abiotic stress tolerance in crop plants. *Plant Physiol. Biochem.* 48, 909-930.
- 22 Giovannetti, M., Mosse, B., 1980. An evaluation of techniques for measuring
23 vesicular-arbuscular infection in roots. *New Phytol.* 84, 489-500.
- 24 Gollack, D., Li, C., Mohanand, H., Probst, N., 2014. Tolerance to drought and salt
25 stress in plants: unraveling the signaling networks. *Front. Plant Sci.* 5, 151.

- 1 Hachez, C., Besserer, A., Chevalier, A.S., Chaumont, F., 2013. Insights into plant
2 plasma membrane aquaporin trafficking. *Trends Plant Sci.* 18, 344-352.
- 3 Hachez, C., Moshelion, M., Zelazny, E., Cavez, D., Chaumont, F., 2006. Localization
4 and quantification of plasma membrane aquaporin expression in maize primary
5 root: a clue to understanding their role as cellular plumbers. *Plant Mol. Biol.* 62,
6 305-323.
- 7 Hajiboland, R., Aliasgharzadeh, N., Laiegh, S.F., Poschenrieder, C., 2010.
8 Colonization with arbuscular mycorrhizal fungi improves salinity tolerance of
9 tomato (*Solanum lycopersicum* L.) plants. *Plant Soil* 331, 313-327.
- 10 Hoagland, D.R., Arnon, D.I., 1950. The water-culture method for growing plants
11 without soil. *Cal. Agric. Exp. Stat. Circ.* 347, 1-32.
- 12 Javot, H., Maurel, C., 2002. The role of aquaporins in root water uptake. *Ann. Bot.* 90,
13 301-313.
- 14 Johansson, I., Karlsson, M., Shukla, V.K., Chrispeels, M.J., Larsson, C., Kjellbom, P.,
15 1998. Water transport activity of the plasma membrane aquaporin PM28A is
16 regulated by phosphorylation. *Plant Cell* 10, 451-459.
- 17 Kaushal, M., Wani, S.P., 2016. Plant-growth-promoting rhizobacteria: drought stress
18 alleviators to ameliorate crop production in drylands. *Ann. Microbiol.* 66, 35-42.
- 19 Kishor, P.B., Sreenivasulu, N., 2014. Is proline accumulation *per se* correlated with
20 stress tolerance or is proline homeostasis a more critical issue? *Plant, Cell Environ.*
21 37, 300-311.
- 22 Kruger, M., Kruger, C., Walker, C., Stockinger, H., Schussler, A., 2012. Phylogenetic
23 reference data for systematics and phylotaxonomy of arbuscular mycorrhizal fungi
24 from phylum to species level. *New Phytol.* 193, 970-984.

- 1 Lee, S.H., Calvo-Polanco, M., Chung, G.C., Zwiazek, J.J., 2010. Cell water flow
2 properties in root cortex of ectomycorrhizal (*Pinus banksiana*) seedlings. *Plant,*
3 *Cell Environ.* 33, 769-780.
- 4 Lehto, T., Zwiazek, J.J., 2011. Ectomycorrhizas and water relations of trees: a review.
5 *Mycorrhiza* 21, 71-90.
- 6 Li, T., Hu, Y-J., Hao, Z-P., Li, H., Wang, Y-S., Chen, B-D., 2013. First cloning and
7 characterization of two functional aquaporin genes from an arbuscular mycorrhizal
8 fungus *Glomus intraradices*. *New Phytol.* 197, 617-630.
- 9 Li, D-D., Ruan, X-M., Zhang, J., Wu, Y-J., Wang, X-L., Li, X-B., 2013. Cotton plasma
10 membrane intrinsic protein 2s (PIP2s) selectively interact to regulate their water
11 channel activities and are required for fiber development. *New Phytol.* 199, 695-
12 707.
- 13 Li, Y.S., Mao, X.T., Tian, Q.Y., Li, L.H., Zhang, W.H., 2009. Phosphorus deficiency-
14 induced reduction in root hydraulic conductivity in *Medicago falcata* is associated
15 with ethylene production. *Environ. Exp. Bot.* 67, 172-177.
- 16 Liu, T., Sheng, M., Wang, C.Y., Chen, H., Li, Z., Tang, M., 2015. Impact of arbuscular
17 mycorrhizal fungi on the growth, water status, and photosynthesis of hybrid poplar
18 under drought stress and recovery. *Photosynthetica* 53, 250-258.
- 19 Malusá, E., Sala, G., Chitarra, W., Bardi, L., 2013. Improvement of response to low
20 water availability in maize plants inoculated with selected rhizospheric microbial
21 consortia under different irrigation regimes. *Environ. Quality* 12, 13-21.
- 22 Marulanda, A., Azcón, R., Chaumont, F., Ruíz-Lozano, J.M., Aroca, R., 2010.
23 Regulation of plasma membrane aquaporins by inoculation with a *Bacillus*
24 *megaterium* strain in maize (*Zea mays* L.) plants under unstressed and salt-
25 stressed conditions. *Planta* 232, 533-543.

1 Maurel, C., Verdoucq, L., Luu, D.T., Santoni, V., 2008. Plant aquaporins: membrane
2 channels with multiple integrated functions. *An. Rev. Plant Biol.* 59, 595-624.

3 Maurel, C., Boursiac, Y., Luu, D.T., Santoni, V., Shahzad, Z., Verdoucq, L., 2015.
4 Aquaporins in plants. *Physiol. Rev.* 95, 1321-1358.

5 Miller, G., Suzuki, N., Ciftci-Yilmaz, S., Mittler, R., 2010. Reactive oxygen species
6 homeostasis and signalling during drought and salinity stress. *Plant, Cell Environ.*
7 33, 453-467.

8 Monforte, A.J., Asins, M.J., Carbonell, E.A., 1997. Salt tolerance in *Lycopersicon*
9 species. 5. Does genetic variability at quantitative trait loci affect their analysis?
10 *Theor. Appl. Genet.* 95, 284-293.

11 Morgan, J.M., 1984. Osmoregulation and water stress in higher plants. *An. Rev.*
12 *Plant Physiol.* 33, 299-319.

13 Noctor, G., Mhamdi, A., Foyer, C.H., 2014. The roles of reactive oxygen metabolism
14 in drought: Not so cut and dried. *Plant Physiol.* 164, 1636-1648.

15 Porcel, R., Redondo-Gómez, S., Mateos-Naranjo, E., Aroca, R., García, R., Ruiz-
16 Lozano, J.M., 2015. Arbuscular mycorrhizal symbiosis ameliorates the optimum
17 quantum yield of photosystem II and reduces non-photochemical quenching in rice
18 plants subjected to salt stress. *J. Plant Physiol.* 185, 75-83.

19 Porcel, R., Ruíz-Lozano, J.M., 2004. Arbuscular mycorrhizal influence on leaf water
20 potential, solute accumulation, and oxidative stress in soybean plants subjected to
21 drought stress. *J. Exp. Bot.* 55, 1743-1750.

22 Prado, K., Boursiac, Y., Tournaire-Roux, C., Monneuse, J.M., Postaire, O., Da Ines,
23 O., Schäffner, A.R., Hem, S., Santoni, V., Maurel, C., 2013. Regulation of
24 *Arabidopsis* leaf hydraulics involves light-dependent phosphorylation of
25 aquaporins in veins. *Plant Cell* 25, 1029-1039.

1 Prak, S., Hem, S., Boudet, J., Viennois, G., Sommerer, N., Rossignol, M., Maurel, C.,
2 Santoni, V., 2008. Multiple phosphorylations in the C-terminal tail of plant plasma
3 membrane aquaporins: role in subcellular trafficking of AtPIP2;1 in response to
4 salt stress. *Mol. Cell Proteom.* 7, 1019-1030.

5 Ruiz-Lozano, J.M., 2003. Arbuscular mycorrhizal symbiosis and alleviation of osmotic
6 stress. *New perspectives for molecular studies. Mycorrhiza* 13, 309-317.

7 Ruiz-Lozano, J.M., Alguacil, M.M., Bárzana, G., Vernieri, P., Aroca, R., 2009.
8 Exogenous ABA accentuates the differences in root hydraulic properties between
9 mycorrhizal and non mycorrhizal maize plants through regulation of PIP
10 aquaporins. *Plant Mol. Biol.* 70, 565-579.

11 Ruiz-Lozano, J.M., Aroca, R., Zamarreño, A.M, Molina, S., Andreo-Jiménez, B.,
12 Porcel, R., García-Mina, J.M., Ruyter-Spira, C., López-Ráez, J.A., 2016.
13 Arbuscular mycorrhizal symbiosis induces strigolactone biosynthesis under
14 drought and improves drought tolerance in lettuce and tomato. *Plant, Cell Environ.*
15 39, 441-452.

16 Ruiz-Lozano, J.M., Perálvarez, M.C., Aroca, R., Azcón, R., 2011. The application of a
17 treated sugar beet waste residue to soil modifies the responses of mycorrhizal and
18 non mycorrhizal lettuce plants to drought stress. *Plant Soil* 346, 153-166.

19 Ruiz-Lozano, J.M., Porcel, R., Bárzana, G., Azcón, R., Aroca, R., 2012. Contribution
20 of arbuscular mycorrhizal symbiosis to plant drought tolerance. State of the art, in:
21 Aroca, R. (Ed.) *Plant Responses to Drought Stress: From Morphological to*
22 *Molecular Features.* Springer-Verlag, Heidelberg, Germany, pp. 335-362.

23 Ruzzi, M., Aroca, R., 2015. Plant growth-promoting rhizobacteria act as biostimulants
24 in horticulture. *Sci. Hort.* 196, 124-134.

1 Sánchez-Romera, B., Ruiz-Lozano, J.M., Zamarreño, A.M., García-Mina, J.M., Aroca,
2 R., 2016. Arbuscular mycorrhizal symbiosis and methyl jasmonate avoid the
3 inhibition of root hydraulic conductivity caused by drought. *Mycorrhiza* 26, 111-122.

4 Scheibe, R., Beck, E., 2011. Drought, desiccation, and oxidative stress, in: Lüttge U.,
5 Beck, E., Bartels, D. (Eds.) *Plant Desiccation Tolerance*, Ecological Studies,
6 Springer-Verlag, Berlin, pp. 209-231,

7 Schwarz, D., Rouphael, Y., Colla, G., Venema, J.H., 2010. Grafting as a tool to
8 improve tolerance of vegetables to abiotic stresses: Thermal stress, water stress
9 and organic pollutants. *Sci. Hort.* 127, 162-171.

10 Sheng, M., Tang, M., Chen, H., Yang, B.W., Zhang, F.F., Huang, Y.H., 2008.
11 Influence of arbuscular mycorrhizae on photosynthesis and water status of maize
12 plants under salt stress. *Mycorrhiza* 18, 287-296.

13 Singh, L.P., Gill, S.G., Tuteja, N., 2011. Unravelling the role of fungal symbionts in
14 plant abiotic stress tolerance. *Plant Signal. Behav.* 6, 175-191.

15 Singh, D.K., Sale, P.W.G., Pallaghy, C.K., Singh, V. 2000. Role of proline and leaf
16 expansion rate in the recovery of stressed white clover leaves with increased
17 phosphorus concentration. *New Phytol.* 146, 261-269.

18 Steudle, E., Peterson, C.A., 1998 How does water get through roots? *J. Exp. Bot.* 49,
19 775-788.

20 Stockinger, H., Walker, C., Schüßler, A., 2009. "*Glomus intraradices* DAOM197198",
21 a model fungus in arbuscular mycorrhiza research, is not *Glomus intraradices*.
22 *New Phytol.* **183**, 1176-1187

23 Trenberth, K.E., Dai, A., Van Der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R.,
24 Sheffield, J., 2014. Global warming and changes in drought. *Nature Clim. Chan.* 4,
25 17-22.

1 Valentine, A.J., Mortimer, P.E., Lintnaar, A., Borgo, R., 2006. Drought responses of
2 arbuscular mycorrhizal grapevines. *Symbiosis* 41, 127-133.

3 Vandeleur, R.K., Sullivan, W., Athman, A., Jordans, C., Gilliam, M., Kaiser, B.N.,
4 Tyerman, S.D., 2014. Rapid shoot-to-root signalling regulates root hydraulic
5 conductance via aquaporins. *Plant Cell Environ.* 37, 520-538.

6 Zelazny, E., Borst, J.W., Muylaert, M., Batoko, H., Hemminga, M.A., Chaumont, F.,
7 2007. FRET imaging in living maize cells reveals that plasma membrane
8 aquaporins interact to regulate their subcellular localization. *Proc. Nat. Acad. Sci.*
9 USA 104, 12359-12364.

10 Zoppellari, F., Malusá, E., Chitarra, W., Lovisolo, C., Spanna, F., Bardi, L., 2014.
11 Improvement of drought tolerance in maize (*Zea mays* L.) by selected rhizospheric
12 microorganisms. *Ital. J. Agromet.* 1, 5-18.

13 Zou, X., Jiang, Y., Liu, L., Zhang, Z., Zheng, Y., 2010. Identification of transcriptome
14 induced in roots of maize seedlings at the late stage of waterlogging. *BMC Plant*
15 *Biol.* 10, 189.

16

17

1 **Table 1.** Pearson correlations between root
 2 hydraulic conductivity (L_{pr}) and PIP root protein
 3 abundance and phosphorylation state in plants from
 4 RIL20 and RIL66.

RIL20	PIP1	PIP2	PIP2₂₈₀	PIP2₂₈₀₋₂₈₃
L_{pr}	0.687	0.590	0.637	0.629
P	0.0001*	0.0004*	0.0001*	0.0001*
RIL66	PIP1	PIP2	PIP2₂₈₀	PIP2₂₈₀₋₂₈₃
L_{pr}	-0.012	-0.693	-0.688	-0.562
P	0.9678	0.0059*	0.0064*	0.0364*

5

6

7

8

1 **Fig. 1S.** (A) Percentage of mycorrhizal root length and (B) number of bacteria on
2 roots of tomato plants (estimated as Log CFU g⁻¹ root fresh weight). A commercial
3 tomato cultivar (Boludo) and four tomato recombinant inbred lines (RIL20, RIL40,
4 RIL66 and RIL100) remained as uninoculated controls (Control) or were inoculated
5 either with the arbuscular mycorrhizal fungus *Rhizophagus irregularis* (AM), the plant
6 growth promoting rhizobacteria *Variovorax paradoxus* 5C-2 (PGPR) or a combination
7 of both microorganisms (AM+PGPR). Plants were cultivated under well-watered
8 conditions or subjected to drought stress for four weeks. Bars represent means ±
9 standard error (n=5). **Within each recombinant inbred line**, different letters indicate
10 significant differences (P<0.05), as determined by Tuckey's test. CFU, colony forming
11 units.

12
13 **Fig. 1.** Shoot dry weight of tomato plants. A commercial tomato cultivar (Boludo) and
14 four tomato recombinant inbred lines (RIL20, RIL40, RIL66 and RIL100) remained as
15 uninoculated controls (Control) or were inoculated either with the arbuscular
16 mycorrhizal fungus *Rhizophagus irregularis* (AM), the plant growth promoting
17 rhizobacteria *Variovorax paradoxus* 5C-2 (PGPR) or a combination of both
18 microorganisms (AM+PGPR). Plants were cultivated under well-watered conditions
19 or subjected to drought stress for four weeks. Bars represent means ± standard error
20 (n=5). **Within each recombinant inbred line**, different letters indicate significant
21 differences (P<0.05), as determined by Tuckey's test.

22
23 **Fig. 2.** (A) Net photosynthetic activity and (B) relative chlorophyll content in tomato
24 plants. See legend for Figure 1.

25

1 **Fig. 3.** (A) Oxidative damage to lipids and (B) proline content in shoots of tomato
2 plants. See legend for Figure 1.

3

4 **Fig. 4.** Root hydraulic conductivity in tomato plants. See legend for Figure 1.

5

6 **Fig. 5.** (A) Relative amounts of un-phosphorylated PIP1 proteins and (B) un-
7 phosphorylated PIP2 proteins in roots of tomato plants (n=3). See legend for Figure 1.

8

9 **Fig. 6.** (A) Relative amounts of phosphorylated PIP2 proteins at Ser280 and (B)
10 phosphorylated PIP2 proteins at Ser280/Ser283 in roots of tomato plants (n= 3). See
11 legend for Figure 1.

12