

# LINKING CROP WATER PRODUCTIVITY TO SOIL PHYSICAL, CHEMICAL AND MICROBIAL PROPERTIES

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## KEYWORDS

crop water productivity, crop yield, soil chemical properties, soil microbial properties, soil physical properties, water consumption

## HIGHLIGHTS

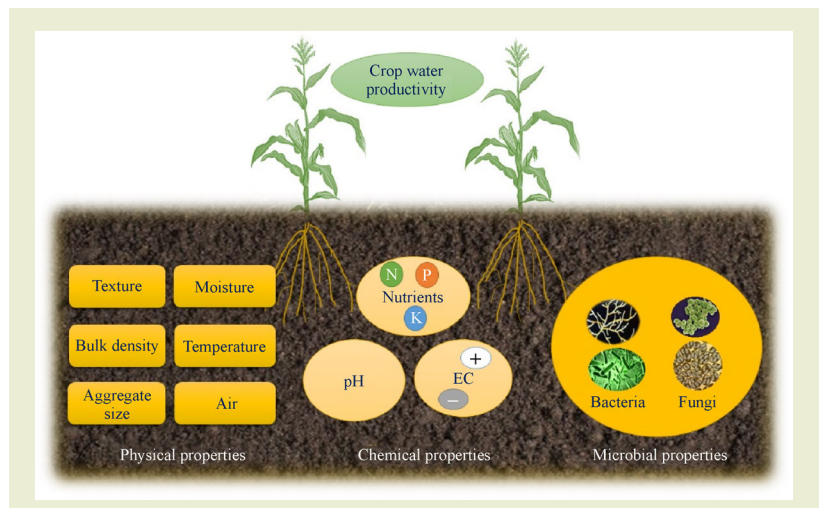
- The linkage between crop water productivity and soil properties were summarized.
- Knowledge of soil microbial effects on crop water productivity is still limited.
- Knowledge of interactions of soil factors on crop water productivity is still limited.

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## GRAPHICAL ABSTRACT



## ABSTRACT

Agriculture uses a large proportion of global and regional water resources. Due to the rapid increase of population in the world, the increasing competition for water resources has led to an urgent need in increasing crop water productivity for agricultural sustainability. As the medium for crop growth, soils and their properties are important in affecting crop water productivity. This review examines the effects of soil physical, chemical, and microbial properties on crop water productivity and the quantitative relationships between them. A comprehensive view of these relationships may provide important insights for soil and water management in arable land for agriculture in the future.

## 1 INTRODUCTION

The annual total water consumption comprising agricultural water, industrial water and domestic water has increased from 580 km<sup>3</sup> in 1900 to 3900 km<sup>3</sup> in 2010 worldwide<sup>[1]</sup>. It resulted in

a substantial decline in the availability of water resources globally<sup>[1]</sup>. The water consumed by agriculture represents nearly 70% of the total freshwater consumption, of which irrigation accounts for the largest share<sup>[1]</sup>. Crop water productivity represents the crop yield per unit of water

consumed<sup>[2]</sup>. A larger crop water productivity indicates higher agricultural production with less water. Therefore, a comprehensive understanding of crop water productivity is imperative to develop a more sustainable agriculture with higher productivity, lower water consumption and healthier environment<sup>[3]</sup>.

The understanding of crop water productivity has continued to change over the past 60 years. Initially, a linear relationship was found between dry matter production and transpiration<sup>[4]</sup>. Crop water productivity was initially defined as the ratio of average dry matter or marketable crop weight produced per unit area and evapotranspiration required<sup>[5]</sup>. Subsequently, with an expanding population and scarce water resources, greater attention has been given to the economic output of agricultural water resources. Against this background the International Water Management Institute proposed a definition of crop water productivity<sup>[6]</sup> that refers to crop yield generated per unit of water consumption. Crop water productivity can be measured and calculated at three scales, i.e. the leaf, the field and the ecosystem. Each of these scales has a different definition of water productivity commonly used at that scale. Water productivity at the leaf scale refers to the ratio between net photosynthetic rate and transpiration rate. At the field scale it is defined as the total crop biomass or yield produced per unit of water during the crop growing period. At the ecosystem scale, water productivity is calculated as the ratio between net ecosystem productivity and ecosystem evapotranspiration<sup>[2]</sup>.

Based on this understanding of crop water productivity great efforts have been made to further explore the effects of various factors on crop water productivity, to provide deeper insights into the mechanisms regulating crop water productivity, and also to provide better capability to predict crop water productivity. Studies reveal that numerous factors can affect crop water productivity, including climate<sup>[7]</sup>, crop species and cultivar<sup>[8]</sup>, field management<sup>[3]</sup> and soil properties<sup>[7]</sup>.

Our group has analyzed the contributions made by all these factors at different scales using the partial least square regression method in Hexi Corridor, Gansu province, north-west China. At the field scale the silt, soil water, and soil available nitrogen rates were positively correlated with yield. In contrast, the sand content and soil electrical conductivity were negatively correlated with yield<sup>[9]</sup>. The contribution rate of soil properties to the irrigation water productivity was about 32.6% at the irrigation district scale, and it increased to 63.4% at the watershed scale. This indicates the important influence of soil properties on crop yield and water productivity<sup>[10]</sup>.

The effects of soil properties on crop water productivity can be more complex than those of climate, crop species and cultivars, and field management. There are numerous abiotic properties in soils, comprising physical properties (e.g., texture, bulk density, moisture content and temperature) and chemical properties (e.g., soil organic carbon content, soil nitrogen content, pH and electrical conductivity). Soils also possess the largest biodiversity of biotic communities in the biosphere, with bacteria, fungi (including mycorrhizas), actinomycetes and nematodes<sup>[11]</sup>. These physical, chemical and biotic properties interact tightly with each other and have interactive effects on the carbon and water cycles in agricultural ecosystems<sup>[12]</sup>.

Additionally, climate and field management can influence crop water productivity by affecting various soil properties. Collectively, the great number of properties in soils and the close interaction among these properties as well as with climate and field management limit us from having a comprehensive insight into linkages between crop water productivity and soil properties. It is therefore essential to gain a comprehensive understanding of the effects of soil properties on crop water productivity by reviewing previous associated studies. Here, we aim to explore three main scientific issues: (1) the effects of soil physical properties on crop water productivity, (2) how soil chemical properties affect crop water productivity, and (3) the effects of soil microbial properties on crop water productivity.

## 2 LINKAGE BETWEEN CROP WATER PRODUCTIVITY AND SOIL PHYSICAL PROPERTIES

### 2.1 Effects of soil texture on crop water productivity

Soil texture refers to the proportions of different-sized particles in a soil. According to the US Department of Agriculture Classification System, soil textural classes comprise coarse sandy soils (sands and loamy sands), moderately coarse loamy soils (sandy loams and fine sandy loams), medium loamy soils (very fine sandy loams, loams, silt loams and silts), moderately fine loamy soils (sandy clay loams, silty clay loams and clay loams) and fine clayey soils (sandy clays, silty clays and clays)<sup>[12]</sup>. Concerning the effects of soil physical properties on crop water productivity, soil texture is a primary factor that influences soil water retention and infiltration capacity, crop root distribution and uptake of water and nutrients<sup>[13]</sup>.

Generally, loamy soils are conducive to a higher crop water

productivity. This has been found for various kinds of crops including grain crops and industrial crops in different studies. Comparative field experiments have produced significantly higher crop water productivity in maize<sup>[14]</sup>, soybean<sup>[15]</sup>, wheat and other crops<sup>[16]</sup> when they were grown in loamy soils. Another approach to evaluate the effects of soil texture on crop water productivity is model simulation. Using a range of crop models (e.g., the CropSyst model, the STICS model and the CERES-Wheat crop-growth simulation model), increased crop water productivity in loamy soils (especially silt loamy soils) has also been found in diverse crops such as maize<sup>[17]</sup> and wheat<sup>[18]</sup>. The reason why loamy soils generally support a higher crop water productivity is mainly associated with the following two aspects. One is that loamy soils generally have more available water and allow easier soil water movement<sup>[19]</sup>. Another aspect is that loamy soils can potentially promote root development and thus enhance water uptake<sup>[16]</sup>. Crops grown in soils with low water holding capacity (e.g., sand and loamy sand) may not respond to nitrogen applications<sup>[20]</sup>, and this limits the increase in crop water productivity.

Evidence in support of the effects of loamy soils on crop water productivity from a typical long-term experiment shows that clayey soils are more likely to reduce crop water productivity<sup>[21]</sup>. Specifically, the water productivity of multiple crops, namely potato, maize, sunflower, and sugar beet, grown in clay soil declined significantly by 22%–25% compared to crops grown in loam soil<sup>[21]</sup>. The decline in water productivity in maize was primarily attributed to a decrease in yield, while the decline in other crops resulted mainly from the balance between a significant decrease in yield and a significant decrease in evapotranspiration. Although statistically non-significant, an apparent decline in crop water productivity was also detected in soybean and tomato grown in clay soil<sup>[21]</sup>. A coherent explanation for the decline in crop water productivity may be that a deficit of water uptake occurred in the crops grown in clay soil during the peak growing season, and this is supported by observations of stomatal conductance, leaf surface evaporation and daily evapotranspiration<sup>[21]</sup>.

Although most crops grow more in loamy soils, there are crops that are more suitable for clayey or sandy soils. Specifically, the rice grain yield in a clay soil was found to be 46% higher than that in a sandy loam soil across cultivars and irrigation treatments<sup>[22]</sup>. In a similar fashion to grain yield, the rice water productivity in a clay soil was found to be 25% higher than in a sandy loam soil<sup>[22]</sup>. These results indicate that rice grows better in clayey soils. In contrast to rice, potato grows better in sandy soils. A previous study shows that potato grown in loamy sand soil produced significantly higher fresh yield than that

planted in coarse sand or sandy loam soils, largely due to higher leaf area indexes, higher rates of photosynthesis and a stay-green effect late in the growing season<sup>[23]</sup>. The water productivity of different crops in different soil textures is summarized in Table 1. Generally, a relative high clay content can have a negative effect on water productivity, and loam soils can be more conducive to plant growth. For instance, maize, quinoa, soybean and tomato have a greater water productivity in loam soils, and higher clay or sand contents is less recommended for these crops (Table 1). However, clay or clay loam soils are suitable for rice (Table 1). Loam soils are suitable for wheat. Sandy soils are a better choice for cotton, potato, and sunflower (Table 1). Different irrigation strategies and soil management should therefore be adopted for different crop species on different soil types across multiple environments.

## 2.2 Effects of soil bulk density and aggregate size on crop water productivity

Soil bulk density can significantly affect soil porosity and consequently influence soil water retention, soil moisture infiltration, water transport characteristics and soil hydraulic properties, thus potentially affecting crop yield and water productivity. Soil bulk densities have been found to be closely associated with soil texture and soil organic matter content<sup>[29]</sup>. In general, the bulk density is greater in sandy soils but low in clayey soils. Also, soils with high organic matter contents have low bulk densities<sup>[29]</sup>. These soil types have loose soil textures that benefit crop growth. A pot experiment with different bulk densities (1.4, 1.6, and 1.8 g·cm<sup>-3</sup>) showed that maize growth and yield were restricted by high bulk density, and shoot dry weight, leaf area, and shoot apex height were significantly higher under the moderate bulk density of 1.6 g·cm<sup>-3</sup><sup>[30]</sup>. A moderate soil bulk density can be suitable to increase crop yield and water productivity. Soil bulk density that is either too high or too low reduced crop water productivity<sup>[30]</sup>. When soil bulk density is too high, soil moisture content can decline and mechanical resistance increase<sup>[31]</sup>. Also, high bulk density can influence root elongation rate thus decreasing the total root length. When growing in hard soils, roots will send signals to the plant to reduce the expansion rate and the stomatal conductance of the leaves<sup>[13]</sup>. High bulk density can also decrease soil aeration and the microbial population<sup>[32]</sup>. The numbers of microorganisms and enzyme activities therefore decrease with increasing soil depth. However, when the soil bulk density is too low, it is easier for water to evaporate at the soil surface and to readily percolate into the subsoil, and this can adversely affect crop water productivity<sup>[31]</sup>.

Theoretically, most of the soil physical properties affecting crop

Table 1 Water productivity (WP) of different crops in relation to soil texture

Crop	Study	Soil texture	Location	Reference	WP (kg·m <sup>-3</sup> )
Wheat	1	Silt loam	Simulation results	[24]	1.21
		Sandy loam			1.14
		Loamy sand			1.05
Rice	2	Clay	Beaumont, Texas, USA	[22]	0.50
		Sandy loam			0.40
Maize	3	Clay soil	Murewa, Zimbabwe	[25]	1.56
		Sandy soil			0.80
Maize	4	Clay	Mediterranean region	[21]	0.87
		Loam			1.13
Sunflower	5	Clay	Mediterranean region	[21]	0.18
		Loam			0.24
Sunflower	6	Clay loam	Bushland, Texas, USA	[26]	0.44
		Silt loam			0.46
		Sandy loam			0.50
		Fine sand			0.54
Potato	7	Sandy loam	Foulum, Denmark	[23]	20.40
		Loamy sand			21.40
		Corase sand			24.00
Potato	8	Clay	Mediterranean region	[21]	16.10
		Loam			21.00
Potato	9	Sandy loam	Ludhiana, India	[27]	13.64
		Loamy sand			12.33
Quinoa	10	Sand	Foulum, Denmark	[28]	1.29
		Sandy loam			1.38
		Sandy clay loam			1.26
Sugar beet	11	Clay	Mediterranean region	[21]	6.11
		Loam			7.85
Cotton (seed)	12	Silt loam	Simulation results	[24]	0.29
		Sandy loam			0.28
		Loamy sand			0.31
Soybean	13	Clay	Mediterranean region	[21]	0.73
		Loam			0.81
Soybean	14	Loamy sand	Ludhiana, India	[15]	0.19
		Sandy loam			0.33
Tomato	15	Clay	Mediterranean region	[21]	8.01
		Loam			8.65

yield can be attributed to soil aggregates<sup>[30]</sup>. Soil aggregate stability is a complex feature influenced by physical, chemical and biological processes in soils. The size of aggregates is an important characteristic that can influence crop growth<sup>[13]</sup>.

Generally, soil aggregates range from < 250 to 2000 µm, and are categorized as micro aggregates (≤250 µm) and macro aggregates (> 250 µm)<sup>[33]</sup>. Crops mostly grow better in soil with small aggregates. For example, maize grew better in pots

containing the smallest aggregates (< 160  $\mu\text{m}$ ) than in those with larger aggregates<sup>[34]</sup>. Cotton and sunflower grew best in soil with 150  $\mu\text{m}$  aggregate size when grown in pots with aggregates ranging from 150 to 1600  $\mu\text{m}$ <sup>[35]</sup>. Although root growth is favored by macro pores, moderate soil porosity can help roots take up more water as well as nutrients and induce positive signals to shoots and leaves. Increased crop yields and water productivities occur only when all the parameters (e.g., soil texture, soil organic matter content, and soil aggregate structure) are appropriate for crop growth and the key requirements in soils (i.e., water, fertilizer, gas and heat) are in balance.

### 2.3 Effects of soil moisture, temperature and air content on crop water productivity

Soil moisture is important in regulating crop water productivity since it can markedly affect crop productivity and evapotranspiration. When soil moisture increases, crop water productivity can be enhanced if the increase in crop productivity is larger than that in evapotranspiration. Conversely, crop water productivity can decline. In support of this point, some studies reveal increasing crop water productivity with increasing soil moisture content<sup>[36,37]</sup>. However, some studies report declines in crop water productivity with higher soil moisture content<sup>[38,39]</sup>, and some other studies show bell-shaped responses of crop water productivity to soil moisture content<sup>[40]</sup> (Table 2).

The effects of soil temperature on crop water productivity were explored under multiple crop management practices such as intercropping and mulching. Intercropping can significantly reduce soil temperatures, increasing soil moisture content and radiation use efficiency and ultimately elevating crop water productivity<sup>[41]</sup>. Mulching is also an important agricultural management practice that affects soil temperature<sup>[42]</sup> and generally increases crop water productivity<sup>[32,42,43]</sup>. Increased crop water productivity can occur with a reduced soil temperature possibly due to positive effects on soil moisture content<sup>[32,42]</sup>. However, increased crop water productivity can

also occur under an increase in soil temperature possibly due to the positive effect of temperature on plant growth<sup>[32,43]</sup>.

Soil air content can affect root respiration and the water and nutrition uptake ability of roots. A higher soil air content can promote crop growth and root extension, enhance the uptake of irrigation water, and indirectly reduce deep soil leakage, ultimately increase crop water productivity<sup>[44,45]</sup>. Conversely, a lower soil air content can inhibit crop growth. In poorly aerated soils, managements such as appropriate irrigation and drainage strategies and deep plowing can be used to increase the air exchange between the soil and the atmosphere. Besides, aerated irrigation can be used to increase the aeration of the soil by adding oxygen to the root zone<sup>[46]</sup>. Table 3 shows the effects of aerated irrigation on the water productivity of different crops. The results indicate that aerated irrigation can increase water productivity in tomatoes by 74.2%, indicating that tomatoes are particularly responsive to an increase in soil oxygen. In addition, cotton was also sensitive to an increase in soil oxygen content because its water productivity increased by 64.6% with aerated irrigation. In contrast, crops such as pineapple, chickpeas and Japanese green beans did not respond significantly to aeration in the root zone.

## 3 LINKAGE BETWEEN CROP WATER PRODUCTIVITY AND SOIL CHEMICAL PROPERTIES

### 3.1 Effects of soil fertility on crop water productivity

Soil fertility is the ability of soils to provide plant nutrients for crop growth and development<sup>[12]</sup>, and it is linked tightly with crop yield. Soil fertility is also associated with crop water consumption by influencing crop traits such as leaf area index<sup>[49]</sup>. As a result, soil fertility can influence crop water productivity. Currently, the linkage between soil fertility and crop water productivity mainly involves two aspects: relation-

**Table 2** Water productivity (WP) of different crops in relation to soil moisture content

Crop	Study	Location	Soil moisture treatment	Reference	WP ( $\text{kg} \cdot \text{m}^{-3}$ )
Alfalfa	1	Gansu, China	40%–70% $\theta_{FC}$	[38]	2.01–3.64
Alfalfa	2	Gansu, China	0%–75% $\theta_{FC}$	[40]	2.43–3.19
Pearl millet	3	Tehran, Iran	0%–60% $\theta_{AW}$	[39]	2.84–3.44
Wheat	4	Ludhiana, India	55%–85% $\theta_{FC}$	[37]	1.51–1.71
Banana	5	India	40%–80% $\theta_{AW}$	[36]	4.15–10.82

Note:  $\theta_{FC}$ , soil water content at field capacity;  $\theta_{AW}$ , soil water content available between field capacity and wilting point.



**Table 3** Increment in crop water productivity (WP) under aerated irrigation

Crop	Study	Location	Reference	WP increment (%)
Potato	1	Giza, Egypt	[45]	38.5
Potato	2	Giza, Egypt	[45]	34.8
Maize	3	Giza, Egypt	[44]	35.7
Maize	4	Giza, Egypt	[44]	36.0
Wheat	5	Australia	[47]	16.3
Cotton (Seed)	6	Australia	[47]	64.6
Tomato	7	Rockhampton, Australia	[46]	74.2
Pineapple	8	Yeppoon, Australia	[47]	4.3
Chickpea	9	Australia	[48]	4.3
Edamame	10	Australia	[48]	1.9
Pumpkin	11	Australia	[48]	18.9

ships between original (native) soil fertility and soil fertilization on crop water productivity. The effects of soil fertilization on crop water productivity have received greater interest since fertilizer application is a standard practice in crop production that has led to significant increases in yields. Studies concerning the effects of soil fertilization on crop water productivity can further be classified as: (1) effects of inorganic fertilizers (e.g., nitrogen, phosphorus and potassium), (2) effects of organic fertilizers, and (3) interactions between inorganic and organic fertilizers or manures.

The relationships between basic soil fertility and crop water productivity have been investigated in previous studies. Soil organic carbon, a key indicator in basic soil fertility, generally has a positive effect on crop water productivity<sup>[25]</sup>. Some studies found positive relationships between soil total nitrogen as well as total phosphorus and crop yield<sup>[50]</sup>. In addition to total soil organic matter, the relationship between available nutrients and crop water productivity was also examined in a recent study which analyzed data from 118 sampling sites using the partial least squares method in the arid oasis region of north-west China<sup>[10]</sup>. This study shows that soil nitrate and available phosphorus were key factors driving irrigated crop water productivity across this arid agricultural ecosystem.

Nitrogen is a component of proteins, nucleic acids, phospholipids and other organic nitrogen compounds necessary for plant growth and development. These are the functional components on which living cells depend. Nitrogen is therefore called a 'living element'<sup>[12]</sup> and plays a key role in crop growth and possibly in crop water productivity. Based on nitrogen fertilization experiments, most studies show that appropriate

application of nitrogen fertilizers generally increased crop water productivity<sup>[51,52]</sup>. However, if the application was excessive, nitrogen fertilization did not increase crop water productivity and may even have decreased it<sup>[39]</sup>. In addition, nitrogen fertilization that is not excessive may also appear to have an effect on crop water productivity in water-limited environments but this has been found to be non-significant<sup>[12]</sup>. Table 4 presents the water productivity of different crops under different nitrogen application rates and Fig. 1 shows the relationship between nitrogen rate and the water productivity of three crops. Nitrogen application can lead to a wide range of crop water productivities (Table 4). The water productivity of potato ranged from 6.7 to 19.5 kg·m<sup>-3</sup>. Cereal crops also responded to nitrogen fertilization. For example, the water productivity of maize ranged from 0.33 to 2.23 kg·m<sup>-3</sup> and that of rice from 0.50 to 1.85 kg·m<sup>-3</sup>. The water productivity of cotton (seed) ranged from 0.33 to 1.17 kg·m<sup>-3</sup>. These crops showed different responses to different nitrogen rates (Table 4). For example, the effective nitrogen rate for potato ranged from 0 to 340 kg·ha<sup>-1</sup> N (Table 4) and the water productivity of potato increased when the nitrogen rate was within this range but decreased with higher nitrogen rates, fitting a parabolic curve (Fig. 1(a)). Maize (Fig. 1(b)) and rice (Fig. 1(c)) showed similar trends. From the data in our summary, the most appropriate nitrogen rate is about 300 and 200 kg·ha<sup>-1</sup> N, respectively, for maize and rice to obtain the highest water productivity.

Second in importance to nitrogen, phosphorus is another plant macronutrient. Currently, knowledge of the effects of phosphorus fertilization on crop water productivity mostly include the following aspects: (1) phosphorus application can increase crop water productivity<sup>[67]</sup>, (2) phosphorus application at depth

**Table 4** Water productivity (WP) of different crops in relation to nitrogen rate.

Crop	Study	Nitrogen rate (kg·ha <sup>-1</sup> N)	Location	Soil property	Reference	WP (kg·m <sup>-3</sup> )
Potato	1	80–240	Palmerston, New Zealand	pH 5.4; soil bulk density 1.35 g·cm <sup>-3</sup>	[53]	7.0–8.3
Potato	2	160–340	Nubaria region west of Nile Delta of Egypt	Sandy in texture, pH 8.2, EC 0.85 dS·m <sup>-1</sup>	[54]	9.0–19.5
Potato	3	0–225	Ludhiana, India	Sandy loam soil, EC 0.2 dS·m <sup>-1</sup>	[27]	6.7–15.7
Potato	4	90–270	Gansu, China	Soil bulk density 1.50 g·cm <sup>-3</sup>	[55]	9.6–12.8
Maize	5	0–225	Lexington, KY, USA	Mauy silt loam	[56]	0.61–1.66
Maize	6	0–300	Vasto, Chieti, Italy	Clay 40.7%, silt 52.9%, sand 6.4%, soil bulk density 1.25 kg·dm <sup>-3</sup>	[57]	1.46–2.23
Maize	7	0–100	Buenos Aires, Argentina	Sandy-loam, Typic Hapludoll	[58]	0.95–1.48
Maize	8	0–200	Western Uzbekistan	Sandy loam to loam texture, EC 2–12 dS·m <sup>-1</sup>	[59]	0.33–0.95
Cotton (seed)	9	80–200	Pali-Marwar, India	Fine loamy in texture, 1.42 g·cm <sup>-3</sup>	[60]	0.33–0.46
Cotton (seed)	10	50–250	Northern Syria	Clay soil, Chromoxerertic Rhodoxeralf	[61]	0.36–0.80
Cotton (seed)	11	0–240	Station near Hama, Syria	/	[62]	0.50–1.17
Cotton (raw)	12	0–250	Western Uzbekistan	Sandy loam to loam texture, EC 2–12 dS·m <sup>-1</sup>	[59]	0.74–0.97
Cotton (lint)	13	0–240	Shandong, China	Sandy loam	[63]	1.10–1.48
Wheat	14	0–200	Western Uzbekistan	Sandy loam to loam texture, EC 2–12 dS·m <sup>-1</sup>	[59]	0.67–2.15
Rice	15	85–173	Lahijan, Iran	-	[64]	1.16–1.67
Rice	16	0–180	Hubei, China	Silty clay loam	[65]	0.50–1.48
Rice	17	0–270	Guangdong, China	pH 5.5	[66]	0.85–1.85

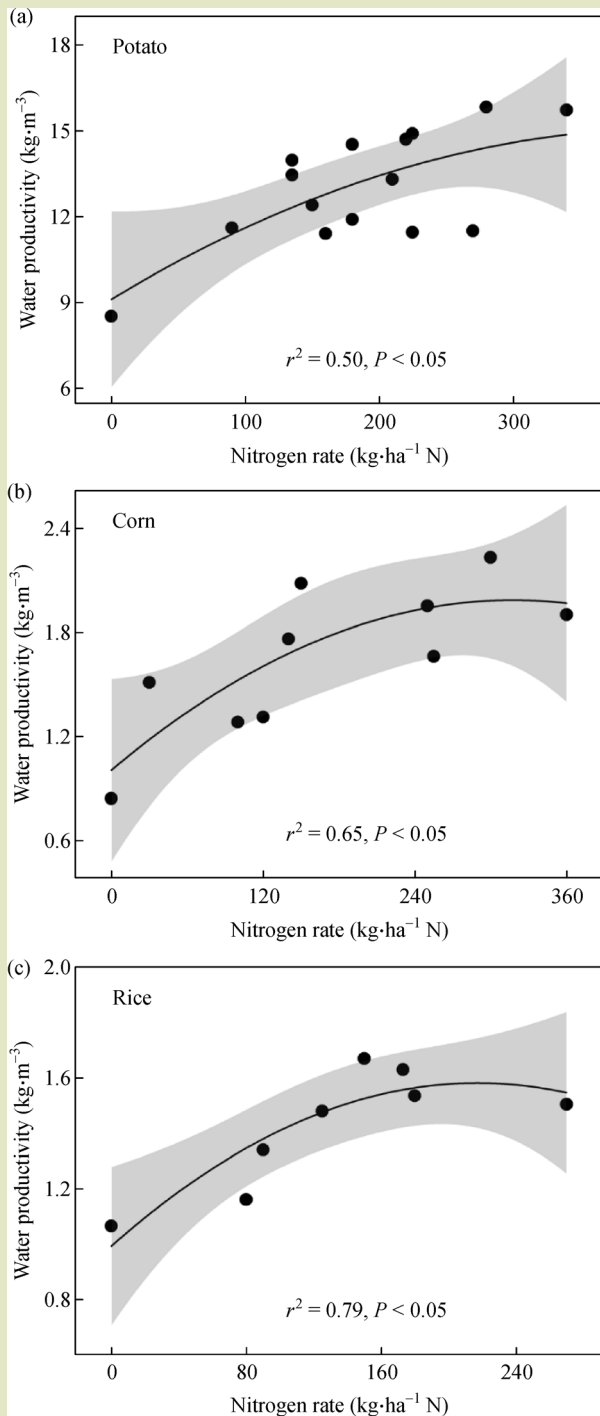
Note: EC, electrical conductivity.

is an effective method to increase crop performance including crop water productivity in semiarid regions<sup>[68]</sup>, and (3) the combination of phosphorus fertilization with arbuscular mycorrhizal fungal inoculation is another effective way to increase crop water productivity<sup>[69]</sup>. In addition to nitrogen and phosphorus, potassium is a plant nutrient that is widely applied in agricultural ecosystems and can promote the synthesis of proteins in plants and increase crop drought resistance<sup>[70]</sup>. Similar to nitrogen and phosphorus, potassium fertilization can increase crop water productivity<sup>[71]</sup>.

Nitrogen, phosphorus and potassium are included in most compound fertilizers and are generally applied simultaneously instead of independently. Therefore, attention should be given to the relative proportions of nitrogen, phosphorus and potassium applied, i.e. balanced fertilization. For this reason, studies have focused on the effect of combined use of nitrogen, phosphorus and potassium fertilizer on crop water productivity. By studying maize water productivity across soil fertility domains on

smallholdings in Zimbabwe, a study found that balanced fertilizer management had an overriding effect on maize crop productivity in soils with soil organic carbon content > 4 g·kg<sup>-1</sup><sup>[72]</sup>. Also, this study found that nitrogen and phosphorus fertilizer are still the most limiting nutrients for maize growth, and in contrast potassium fertilization did not increase grain yields nor did it alter the response of crop production to nitrogen or phosphorus fertilization<sup>[72]</sup>.

Many studies also have focused on effects of organic fertilizers, especially the combined use of organic and inorganic fertilizers, on crop water productivity. Understanding these issues involves the following aspects: (1) appropriate organic amendments in addition to the balanced use of organic and inorganic fertilizers can increase crop water productivity<sup>[73]</sup>, (2) the combination of plastic film mulching and organic and inorganic fertilizers can significantly enhance crop water productivity<sup>[74]</sup>, (3) large amounts of inorganic fertilizers combined with organic manures can decrease crop yields, crop water productivity



**Fig. 1** Relationships between crop water productivity (WP) and nitrogen rates in different crops: (a) potato<sup>[27,54,55]</sup>; (b) maize<sup>[56–59]</sup>; (c) rice<sup>[64,66]</sup>. Solid lines represent the fitted lines and gray areas denote the 95% confidence intervals.

and nitrogen use efficiency while increasing the residual nitrate contents in soils<sup>[75]</sup>.

### 3.2 Effects of soil pH on crop water productivity

Soil pH is a key chemical factor shaping a healthy soil environment for biological activity and is a key variable affecting the forms and availability of nutrients in soils. Soil pH can influence crop water productivity by regulating soil nutrient availability, microbial activity, plant root nutrition and other biogeochemical processes in soils<sup>[76]</sup>. Currently, knowledge of the effects of soil pH on crop water productivity are mainly on the following aspects: (1) effects of liming application on crop water productivity<sup>[77]</sup>, and (2) effects of sulfur application on crop water productivity<sup>[78]</sup>.

Each crop species is adapted to an optimum soil pH range. A soil pH outside this range, either too acidic or too alkaline, can have negative effects on crop growth and hence crop water productivity<sup>[12]</sup>. Soils in tropical and subtropical regions are generally strongly acid largely due to high rainfall and leaching, and this may depress crop growth and water productivity<sup>[79]</sup>. Studies concerning the effects of lime application on crop growth and water productivity were conducted to increase crop water productivity in these acid soils. These studies generally show that the addition of lime to strongly acid soils may enhance crop water productivity, such as with maize in the subtropical north-eastern Himalayas<sup>[77]</sup>, maize/cowpea intercropping in a highly acid tropical soil in Brazil<sup>[80]</sup> and alfalfa in an acid soil in Australia<sup>[81]</sup>.

A soil is considered to be calcareous when its pH is  $> 7.5$ <sup>[12]</sup>. Phosphorus availability is generally low in calcareous soils in which the high soil pH can induce lower phosphorus availability<sup>[12]</sup>. It has been reported that plants cannot survive in soils with pH  $> 10.5$  due to a lack of available phosphorus<sup>[78]</sup>. Soil acidification can be an effective method of ameliorating calcareous soils. Application of sulfur is a widely used method of soil acidification that can alter the physical and chemical properties of calcareous soils so to increase crop yields<sup>[82]</sup>.

### 3.3 Effects of soil electrical conductivity on crop water productivity

Soil electrical conductivity is a measure of the ability of the soil solution to conduct electric current and is widely used to reflect the degree of soil salinity and alkalinity<sup>[12]</sup>. In general, soils with a higher salinity or alkalinity exhibit higher electrical conductivity<sup>[12]</sup>. Saline soils, i.e. soils with excessive soluble salts or exchangeable sodium in the root zone, are widely distributed around the world<sup>[83]</sup>. In addition, salt-affected soils can significantly affect crop growth and water consumption<sup>[84]</sup>. Knowledge of the effects of soil salinity on crop water



productivity is therefore important in increasing crop productivity globally.

Evidence from grain and industrial crops indicates that soils with larger electrical conductivity generally decrease crop water productivity<sup>[85–87]</sup>. For example, the water productivity of maize declined significantly with the application of saline water (4.18 to 9.74 dS·m<sup>-1</sup>) compared to fresh water (1.10 to 2.23 dS·m<sup>-1</sup>) in a saline coastal region of Bangladesh<sup>[86]</sup>. Also, the highest water productivity, irrigation water productivity and yield of cotton occurred in a low salinity soil (17 to 25 mS·cm<sup>-1</sup>) compared to the medium (29 to 50 mS·cm<sup>-1</sup>) and high (52 to 62 mS·cm<sup>-1</sup>) salinity soils in the Tarim River Basin in central Asia<sup>[85]</sup>. A depressed water productivity was found in multiple crops such as snap bean, snow pea, celery and pepper when irrigated with highly saline water<sup>[87,88]</sup>.

Mechanisms involved in the influence of salt stress during crop growth are mainly associated with inhibition of enzyme activity, inhibition of seed germination, restrained growth and differentiation of plant tissues, reduced leaf area and lower rates of photosynthesis. The salinity-induced growth reduction in crops can be biphasic with osmotic stress during the first phase and ion toxicity during the second phase<sup>[89]</sup>. Salt stress during the germination phase can primarily delay the start of germination and disperse germination events by significantly lowering the osmotic potential of the soil to restrict seed water uptake<sup>[84]</sup>. Salinity can also reduce shoot growth by suppressing leaf initiation and expansion<sup>[84]</sup> and rapidly decrease leaf growth rate<sup>[58]</sup>. Salt stress affects stomatal conductance due to perturbed water relations and then decreases rates of crop transpiration and photosynthesis, consequently leading to reduced crop yields. Both transpiration and net photosynthesis rates were observed to decrease in maize under salt stress<sup>[90]</sup>. Sodium toxicity is the major mechanism in the second phase of salt stress. High sodium concentrations in maize can interfere with the uptake of nitrogen, potassium, calcium, magnesium and iron, causing water loss and leading to disturbance in stomatal function. Nitrogen uptake by shoots and grains have been reported to significantly decline at 6 dS·m<sup>-1</sup> salinity in irrigation water<sup>[91]</sup>. Moreover, salt stress can reduce grain weights and numbers in maize, leading to reduce in grain yields and water productivity.

It has been reported that biochar and magnetic treatment of irrigation water can effectively reduce the negative effects induced by saline irrigation water<sup>[92]</sup>. There are two main explanations for this. The first is that biochar can decrease soil osmotic potential and make crops take up more nutrients<sup>[93]</sup>. The second is that biochar has a highly porous structure and

large surface area that can significantly enhance the soil water holding capacity and thus help to mitigate the salt induced osmotic stress and ion toxicity to crops<sup>[94]</sup>. Similar to biochar, magnetic treatment of irrigation water can decrease ions in saline water or recycled water and hence decrease osmotic stress effects on crop growth and production<sup>[92]</sup>. The combination of biochar and fertilization can enhance overall soil quality, further increasing crop yield and water productivity in alkaline soils<sup>[95]</sup>. However, adding biochar can also reduce the supply of available water and hence can generate some negative effects on crop water productivity<sup>[12]</sup>.

## 4 LINKAGES BETWEEN CROP WATER PRODUCTIVITY AND SOIL MICROBIAL PROPERTIES

The soil microbial community is a key driver in biogeochemical cycles of agricultural ecosystems<sup>[11]</sup>. Crop water productivity is an indicator of agricultural ecosystem biogeochemical cycling and may also be influenced by the soil microbial community. Most relevant studies have focused on the effects of root microbial inoculation on crop water productivity<sup>[67,96,97]</sup>. In general, root microbial inoculation such as arbuscular mycorrhizal fungal inoculation, rhizobial inoculation and phosphate solubilizing bacterial inoculation, have all been shown to have positive effects on crop water productivity. There are two main explanations. The first is that crops in agricultural ecosystems have prevailing nutrition limitations, especially nitrogen and phosphorus, largely due to removal at harvest<sup>[98]</sup>. The second is that the microorganisms in the inocula, arbuscular mycorrhizal fungi, rhizobium and phosphate solubilizing bacteria, can promote the decomposition of soil organic matter and the availability of nutrients, thus helping crops take up more nutrients for their growth and development<sup>[99]</sup>. The role of arbuscular mycorrhizal fungi has received the greatest attention<sup>[67,96,97,99]</sup>. This may be because: (1) most crops have arbuscular mycorrhizal fungi, (2) arbuscular mycorrhizal fungi can obtain nutrients as well as water effectively for crops, and (3) arbuscular mycorrhizal fungal inoculation has a potentially wide application in agricultural production<sup>[96,99]</sup>.

When analyzing the effects of root microbial inoculation on crop water productivity, some studies have also examined the interactions between root microbial inoculation and other agronomic management practices on crop water productivity<sup>[67,96,97,99]</sup>. Studies have focused on irrigation, plastic film mulching and phosphorus fertilization. Concerning the interaction with irrigation, microbial inoculation is generally effective in alleviating adverse effects of water stress on crop water

productivity. Furthermore, the combination of microbial inoculation with film mulching can increase crop water productivity<sup>[97]</sup>. Using interactions with phosphorus fertilization, treatments involving microbial inoculation along with phosphorus fertilizer application have been demonstrated to lead to a significantly higher crop water productivity in comparison with non-microbial inoculants<sup>[67,69]</sup>.

In addition to the effects of microbial community inocula on crop water productivity, more attention needs to be given to interactions between the original (native) soil microbial community and crop water productivity. However, knowledge of this aspect remains limited, preventing deeper insights into the effects of soil microbial community on crop water productivity. The continual development of new technologies in microbiology (e.g., metagenomic sequencing and gene probing) will aid the exploration of the relationship between soil microbial community properties and crop water productivity in the future<sup>[11]</sup>.

## 5 CONCLUSIONS

This review summarizes the effects of soil physical, chemical and microbial properties on crop water productivity. In conclusion, physical properties are important in establishing the foundation for crop growth which can influence crop water productivity

through effects on soil moisture content, water transfer, soil aeration and soil temperature. Chemical properties affect crop productivity indirectly through the influence of soil structure, nutrient status, soil pH and reduction-oxidation potential. Regarding microbial properties, the different types of microorganisms in soils affect crop water productivity by promoting the decomposition of soil organic matter and the availability of nutrients. These properties characterize the environment for crop growth that affect crop water productivity independently as well as interactively. In agricultural production systems, suitable combinations of physical and chemical factors can create a healthy environment for microorganisms, which in turn affect the soil physicochemical properties. Further exploration of the influence of soil microbial properties on crop water productivity and the interactions among these three classes of properties (physical, chemical and microbial) on crop water productivity are required. Further studies on the methods for further exploration of the linkages between soil properties and crop water productivity at a regional scale and how to use these linkages in field planning and management are needed. Also, given the potential for separate application of nitrogen through irrigation water (fertigation), its effects on crop water productivity should be examined in the future. Also, taking full consideration of management strategies (e.g. conservation tillage and soil amendments strategies) and climate change is an important way of exploiting the trade-off between soil properties and crop water productivity at field and regional scales.

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### Compliance with ethics guidelines

Di Wu, Allan A. Andales, Hui Yang, Qing Sun, Shichao Chen, Xiuwei Guo, Donghao Li, and Taisheng Du declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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