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REVIEW

How does building healthy soils impact sustainable use of water resources in irrigated agriculture?

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As blue water resources become increasingly scarce with more frequent droughts and overuse, irrigated agriculture faces significant challenges to reduce its water footprint while maintaining high levels of crop production. Building soil health has been touted as an important means of enhancing the resilience of agroecosystems to drought, mainly with a focus in rainfed systems reliant on green water through increases in infiltration and soil water storage. Yet, green water often contributes only a small fraction of the total crop water budget in irrigated agricultural regions. To scope the potential for how soil health management could impact water resources in irrigated systems, we review how soil health affects soil water flows, plant–soil–microbe interactions, and plant water capture and productive use. We assess how these effects could interact with irrigation management to help make green and blue water use more sustainable. We show how soil health management could (1) optimize green water availability (e.g., by increasing infiltration and soil water storage), (2) maximize productive water flows (e.g., by reducing evaporation and supporting crop growth), and (3) reduce blue water withdrawals (e.g., by minimizing the impacts of water stress on crop productivity). Quantifying the potential of soil health to improve water resource management will require research that focuses on outcomes for green and blue water provisioning and crop production under different irrigation and crop management strategies. Such information could be used to improve and parameterize finer scale crop, soil, and hydraulic models, which in turn must be linked with larger scale hydrologic models to address critical water-resources management questions at watershed or regional scales. While integrated soil health-water management strategies have considerable potential to conserve water—especially compared to irrigation technologies that enhance field-level water use efficiency but often increase regional water use—transitions to these strategies will depend on more than technical understanding and must include addressing interrelated structural and institutional barriers. By scoping a range of ways enhancing soil health could improve resilience to water limitations and identifying key research directions, we inform research and policy priorities aimed at adapting irrigated agriculture to an increasingly challenging future.

Keywords: Soil health, Irrigated agriculture, Plant–soil–microbe interactions, Green water, Blue water

Introduction

Irrigated agriculture faces the dual challenge of adapting to a hotter, more drought-prone climate with higher evaporative demand while also reducing its water footprint. Rising temperatures and increases in heat waves and the intensity and frequency of droughts due to climate change (Hatfield et al., 2011; Trenberth et al., 2014) will likely worsen water limitations on crop productivity (Quinteiro et al., 2018). Multiyear droughts reduce water available for irrigation, cause agricultural sector job losses, reduce agricultural output (Howitt et al., 2015), and increase groundwater consumption, accelerating groundwater overdraft and land subsidence (Faunt et al., 2016). Climate change-driven reductions in the snowpack that often provides irrigation water and recharges groundwater exacerbate these overdraws worldwide, particularly important in regions like the Western United States (López-Moreno et al., 2017; Pathak et al., 2018).

Current withdrawals of blue water—water in streams, rivers, lakes, reservoirs, and groundwater aquifers—for agriculture already exceed planetary environmental boundaries (Sposito, 2013; Steffen et al., 2015).

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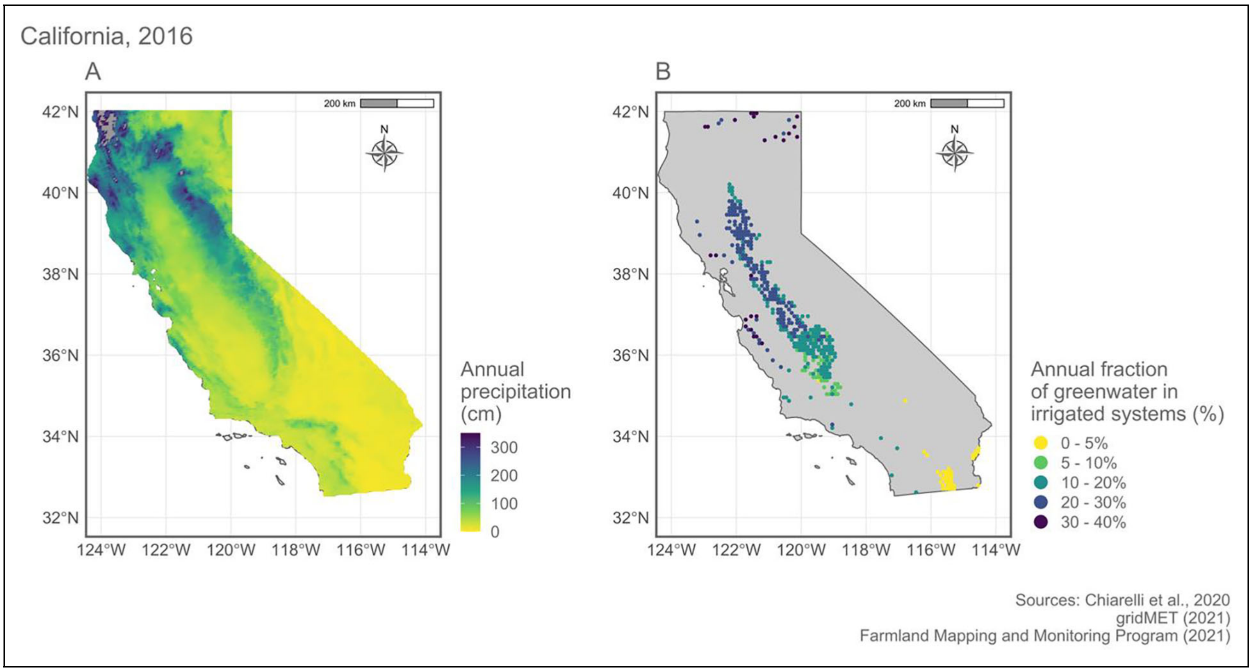

Sources: Chiarelli et al., 2020
gridMET (2021)
Farmland Mapping and Monitoring Program (2021)

Figure 1. Annual precipitation data of California and estimated water requirements (2016). (A) Total annual precipitation (cm). (B) Modeled annual evapotranspiration (ET) fraction derived from green water (%) in irrigated systems. Green crop water requirements represent the amount of ET met by precipitation. Blue water requirements represent the amount of irrigation required to make up the difference between ET and the green crop water requirement, although this may overestimate blue water since in practice the full amount of water required to replace ET is sometimes not provided (e.g., with deficit irrigation). Areas corresponding to Prime Farmlands and Farmland of Statewide Importance were derived from census-based inventories as reported in Portmann et al. (2010) and the Farming Mapping and Monitoring Program (2021). Based on the dataset by Chiarelli et al. (2020) and gridMET (Abatzoglou, 2013; 2021).

Worldwide, irrigated agriculture consumes about 70%–90% of blue water used by humans (Ward and Pulido-Velazquez, 2008), which impacts nonagricultural ecosystems (Rost et al., 2008) and competes with growing demand from other human uses like drinking water and industry. Groundwater provides 43% of total consumptive irrigation water used globally, and reliance on groundwater for irrigation is increasing (Siebert et al., 2010), despite 6%–20% of global groundwater wells already at risk of running dry (Jasechko and Perrone, 2021). Irrigated areas constitute 20% of the total area and 40% of total agricultural production; their continuing expansion dominates global crop blue water consumption, which is expected to increase 70% by 2071–2099 compared to 1971–2000 (Huang et al., 2019). Higher blue water consumption coupled with lower blue water availability due to climate change will lead to approximately 60% of the world population likely experiencing blue water shortages by 2050 (Rockström et al., 2009). Increasing blue water withdrawals to intensify or expand irrigated agriculture thus poses major risks for humans and the nonhuman biosphere (Sposito, 2013).

Alternative sources of irrigation water, such as recycled water (i.e., graywater) or desalinated water, present modest opportunities to reduce blue water use (Assouline et al., 2015). While recycled water irrigates approximately 20 M ha globally (approximately 5% of global irrigated land; Jimenez and Asano, 2008; Meier et al., 2018), strategies to deal with trade-offs, such as salinization in arid and semiarid regions, are needed to make these alternative irrigation water sources more widely viable (Hamilton et al., 2007; Assouline et al., 2015).

Green water may provide underappreciated opportunities to alleviate pressure on blue water withdrawals in irrigated systems. Green water is rainfall that infiltrates in the upper unsaturated soil layers and flows back to the atmosphere through evapotranspiration (ET), that is, it is the water retained in soil after deep percolation and runoff (Falkenmark and Rockström, 2010). Green water accounts for 90% of cropland water consumption globally, including both rainfed and irrigated agriculture (Rost et al., 2008; Sposito, 2013). Even in areas where irrigated agriculture relies largely on blue water, such as Mediterranean regions like California, United States, green water still accounts for 6%–35% of total crop ET (**Figure 1**; Devine and O'Geen, 2019; Chiarelli et al., 2020). Green water has not received much attention from water resources management and planning agencies in irrigated regions in part due to the challenge of quantifying its consumption on a landscape scale and the difficulty in differentiating between green and blue water flows (Jewitt, 2006). Meeting the global challenge of adapting irrigated agriculture to water limitations will involve: (1) reducing the consumption of blue water for irrigation to achieve sustainable levels of withdrawal, (2) optimizing green water availability to crops, and (3) maximizing productive consumption of water from all sources, that is, water that flows as transpiration through plants rather than soil evaporation, all while maintaining crop production.

Soil characteristics are a major mediator of both green and blue water flows, alongside factors like topography and land use (Quinteiro et al., 2018). Inherent soil characteristics like texture strongly govern physical properties important for these flows, such as saturated hydraulic conductivity, water storage capacity, and soil structural stability (Bünemann et al., 2018). Dynamic soil properties like soil structure, that is, those influenced by management on relatively short seasonal to decadal timescales, also affect water flows (Schwen et al., 2011).

With growing multisector interest, soil health is a concept focused on managing dynamic soil properties like soil organic matter (SOM), soil structure, and soil organisms to support soil ecosystem functioning and provide multiple ecosystem services beyond just the provisioning of food, fiber, and fuel, including water provisioning and effective use of water resources (de Groot et al., 2010). Managing soil health is based on several well-defined *principles*—reducing soil disturbance, keeping the soil covered, increasing plant diversity, and keeping living roots in the ground—that manifest as *practices*, such as reduced/no till, cover cropping, organic matter amendments, crop rotation diversification, and strategic integration of perennial plants into key landscape positions. These practices change the dynamic biological, chemical, and physical properties that underlie healthy soils, which affect water provisioning and effective use in multiple ways.

There is a widespread perception among stakeholders, such as farmers, government and academic scientists, and policy advocates, that building healthier soils could play a large role in adapting to reduced and volatile water availability due to its potential for increasing water provisioning (Cano et al., 2018; Wade et al., 2021). Based on studies predominantly in rainfed agriculture, proponents most often argue that soil health-promoting management that increases SOM and improves soil structure will increase soil water holding capacity and infiltration (Lotter et al., 2003; Gaudin et al., 2015; Williams et al., 2016), leading to higher capture and storage of green water available for plants, while also reducing harmful runoff. For instance, an informational campaign from the U.S. Natural Resources Conservation Service asserted in an infographic that “For each 1% increase in organic matter, U.S. cropland could store the amount of water that flows over Niagara Falls in 150 days” (Nichols, 2015). In irrigated agriculture, California’s Fourth Climate Assessment notes benefits of increasing SOM on hydrological flows in croplands, including capturing and storing more water and thus mitigating the impacts of water deficits (Flint et al., 2018).

While infiltration and water storage capacity are crucial, understanding the full potential for healthy soils to promote effective use of water resources requires going beyond just water storage and capture, especially in irrigated agriculture. Since green water accounts for a relatively small proportion of crop water use in irrigated Mediterranean systems (Devine and O’Geen, 2019), it is unclear how important increasing green water availability is relative to other mechanisms by which soil health could impact water provisioning and sustainable water use. How soil health practices impact the soil water balance in such systems must also be considered, for instance, whether ET from cover cropping depletes green water for subsequent crops (DeVincentis et al., 2022). With climate change expected to bring even starker contrasts between wet and dry seasons in Mediterranean regions (Nunes et al., 2019), and urbanization and population growth increasing competition for blue water supplies (Nouri et al., 2019a) scoping the role of soil health management for water conservation is essential for policymaking.

Here, we assess how healthy soils could affect both green and blue water availability and its productive use for crop production, focusing in particular on the complex case of irrigated cropping systems. We first review how healthy soils affect hydrologic processes and soil hydraulic properties, plant–soil–microbe interactions, and plant water demand and uptake in annual and perennial croplands. We include studies conducted in both irrigated and rainfed systems to draw from a wide range of research. We then focus on irrigated systems specifically by proposing strategies for integrated soil health and water management to conserve water resources, as well as trade-offs and social–ecological challenges for making this transition. We highlight examples and lessons from California, where we have experience, with applicability to other irrigated regions. Finally, to assess our current potential for quantitative scenario analysis and planning, we also consider key knowledge gaps and priority areas for future research. In particular, we focus on the extent to which predominant agro-hydrological models adequately capture both impacts of management on water-related soil properties and processes and if these changes in turn impact water resources across scales. By doing so, we aim to inform discussions, improve current knowledge, and suggest ways forward for how to meet the global agricultural water challenge, particularly in ways that could lead to the well-characterized cobenefits of soil health management.

Healthy soils and water provisioning

Soil water flows and storage

Ideally, a healthy soil increases the capture, retention, and provisioning of both green and blue water and thereby enhances crop growth (**Figure 2**). The partitioning of green and blue water is governed by the balance between runoff versus infiltration, percolation, evaporation, and soil water storage (Hoekstra, 2019). Infiltration rates dictate how fast water penetrates the soil surface and thus plays a key role in determining the amount of green water stored in the soil after rains and made available to plants and how much blue water can be applied in an irrigation before runoff occurs. Deep infiltration or percolation contributes to blue water reservoirs by recharging underlying groundwater (O’Geen et al., 2015). Infiltration is controlled by soil pore size distribution and geometry

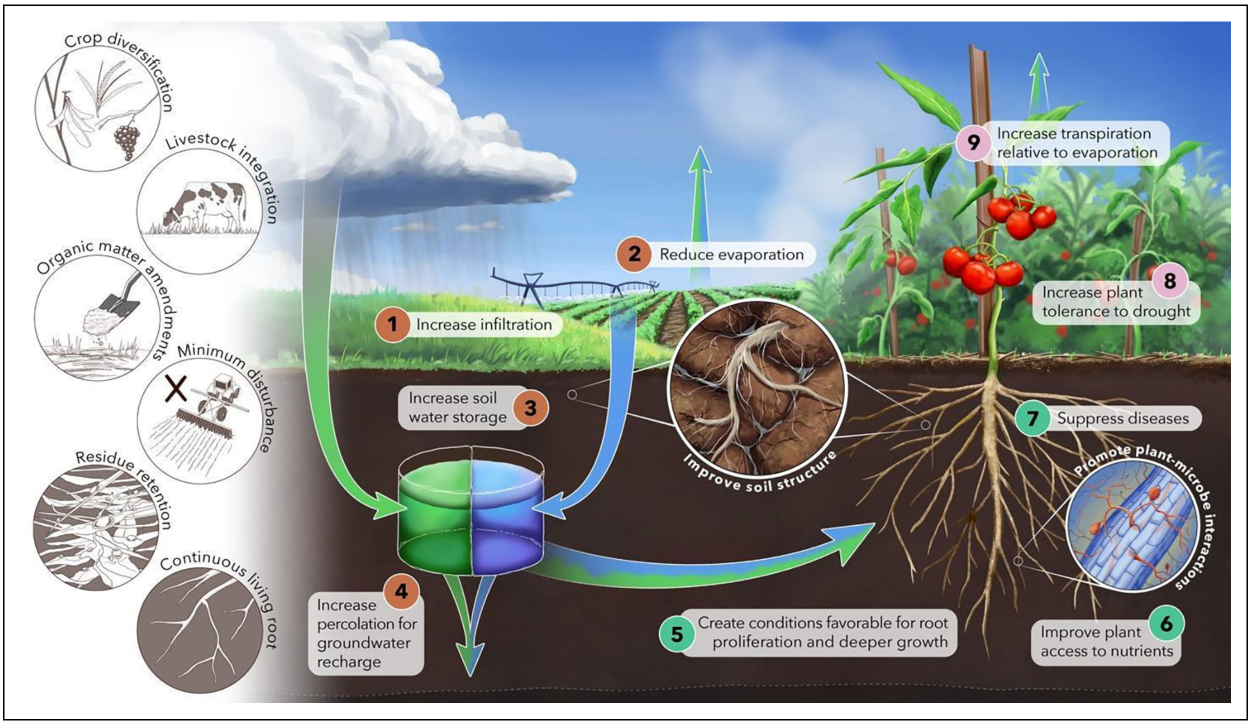

Figure 2. Conceptual framework for outcomes of soil health management for water resources. Hydrologic processes (orange circles) and plant–soil–microbe interactions below (green circles) and aboveground (pink circles) affecting blue and green water use in irrigated systems. Soil health management practices are represented in circles on the left side. Blue arrows indicate blue water flows, and green arrows indicate green water flows. Arrows with both colors represent mixed blue and green water components. Arrow size does not represent the flow magnitude. Original artwork by Elena Harley (www.elabarts.com).

(Pahlavan-Rad et al., 2020) and soil structure (the way in which soil particles are grouped together into aggregates bound together by physical, chemical, and biological processes, which dictate the pore space of the soil system; Fischer et al., 2015).

Several soil health practices—including cover cropping, reducing tillage, organic amendments, crop residue retention, and cropping system diversification—affect one or more soil physical properties related to infiltration (Bagnall et al., 2022). For example, continuous living cover through perennial herbaceous and woody crops and cover crops consistently and strongly promotes higher infiltration rates compared to bare fallow (Alvarez et al., 2017; Basche and DeLonge, 2019). Plant roots strongly influence the interrelated biological, chemical, and physical processes that increase porosity and aggregation (Meurer et al., 2020). For instance, based on a global meta-analysis, perennials increased infiltration rates by 59.2% on average over annuals, with cover crops having the second largest effect size at 34.8% over bare fallow (Basche and DeLonge, 2019). Reducing soil disturbance through no-till may increase or decrease infiltration; a global quantitative synthesis reported no net effect with a wide range of positive and negative outcomes (Basche and DeLonge, 2019). While more consistently positive effects would be expected with the improvement and preservation of soil structure with reduced/no-till, negative outcomes may be due to comparisons being made soon after tillage. In the short term, tillage can temporarily increase infiltration by promoting macropores and reducing soil bulk density (Alegre et al., 1991; Martínez et al., 2008), especially compared to no-till systems that have not been in place for long enough to reestablish highly interconnected pores (Martínez et al., 2008; Strudley et al., 2008). The interaction of soil health practices differentially affects infiltration rates. For example, a meta-analysis found that while no-till in combination with residue retention improves infiltration, tillage in combination with cover cropping does not affect infiltration (Basche and DeLonge, 2019). Organic matter amendments, such as crop residues, straw, biochar, and manure (from integrated crop-livestock systems), often improve soil structure and infiltration (Dong et al., 2022), but effects vary with the sources and degree of decomposition of its components as well as factors like the rate and duration of application and amended soil types (Kranz et al., 2020; Dong et al., 2022). Integrated crop-livestock systems can affect soil structure both positively and negatively (Franzluebbers, 2007; Peterson et al., 2019). High stocking rates and/or poorly timed grazing compacts soil and decreases infiltration, but careful grazing management, especially in perennial pastures, can increase SOM and promote continuous biopores (Franzluebbers, 2007; Peterson et al., 2019). Diversified crop rotations can improve soil structure and infiltration by including crops with deep and shallow roots and by increasing soil cover and root presence in the topsoil (Alhameid et al., 2020).

At the field scale, leveraging soil health management practices to increase infiltration could increase green water storage in the soil during rain events that could be used to delay irrigation during the spring and reduce the amount of runoff from flood irrigation events during the growing season. At the landscape scale, such practices could improve deep percolation and increase blue water in Mediterranean regions via groundwater recharge during winter rains. Percolation, the movement of water through soil by gravity and capillary forces, is an important soil property for conveying water beyond the influence of ET and eventually recharging groundwater. Percolation occurs mainly through interconnected macropores; thus, the texture and structure of a soil, which dictates a soil's pore size distribution and pore connectivity, will strongly control the rate of percolation. Percolation is also influenced by water storage since water potential (the sum of gravitational, osmotic, and matric potentials), and thus water flow, is a function of soil water content (Richards, 1931). Percolation proceeds after soil has reached field capacity and moves toward saturated conditions. Soil health practices that influence SOM, soil structure, and porosity will affect percolation (Dahlke et al., 2018; Basche and DeLonge, 2019). For instance, with higher SOM, clay-organic matter interactions reduce dispersibility of clays and help improve and preserve soil structure, increasing the resilience of aggregates to disturbance and improving infiltration (and thus, eventually, percolation). Improved soil structure also creates a "sponge-like" pore system, where pore size is more evenly distributed across micro to meso to macro pore sizes (de Jonge et al., 2009). This type of pore system can improve the soil's capacity to retain water, as well as percolate water once field capacity is reached. The "sponge-like" hydrological behavior depends on SOM and clay content, and changes in soil management could cause changes in the hydrological services provided (Mosquera et al., 2020). Degraded soils—with poor structure, high macroporosity, and "downpipe-like" pore systems—may contribute to groundwater recharge, and thus blue water reservoirs, via preferential flow. But such soils can also have a large proportion of "dead-end" pore spaces within the broader soil matrix that reduces the capacity of a soil to store green water for plant uptake and can accelerate the movement of contaminants toward aquifers (de Jonge et al., 2009). In certain contexts, soil health practices could also reduce percolation. A meta-analysis found that cover-cropping reduced percolation by 27 mm on average in temperate systems compared to bare-fallow plots (Meyer et al., 2019). Overall, however, few studies specifically measure soil health management impacts on percolation, highlighting a knowledge gap concerning the link between soil health and blue water resources.

Since soil evaporation is a part of nonproductive vertical fluxes (sometimes referred to as "white water"; Jewitt, 2006), reducing soil evaporation relative to crop transpiration promotes productive water flow and increases the percentage of water recharged via percolation when transpiration is low. Plant biomass residues left on the soil surface reduce soil evaporation and increase soil water content and plant available water in drought-prone areas (Turmel et al., 2015). Also, residues can be an effective weed control method (Nichols et al., 2015). However, when precipitation is light and infrequent, surface residues can intercept precipitation and increase subsequent evaporation (Turmel et al., 2015). No-till systems in semiarid areas sometimes reduce evaporation (Strudley et al., 2008; Schwartz et al., 2010; Soane et al., 2012; Jokela and Nair, 2016), but the magnitude and direction of the effect depend on tillage type, when tillage occurred, the timing of precipitation following tillage, and the length of the monitoring period of the study (Strudley et al., 2008; Schwartz et al., 2010; Sun et al., 2018). Decreased evaporation under no-till has been attributed to surface residue retention (Sun et al., 2018); however, other physical changes, such as surface roughness and soil porosity, may be partly responsible (O'Brien and Daigh, 2019). Cover crops similarly reduce evaporation (i.e., via increased surface residues, changes to surface roughness, and soil porosity). But most studies on cover crops and their effects on the soil water balance have been conducted in humid regions (Daryanto et al., 2018). In semiarid regions, where ET can be a large part of the water balance, more research is needed on how cover cropping and other soil health practices affect productive versus nonproductive water flows.

Increases in SOM and subsequent improvements to soil aggregation, pore space distribution, and soil water retention have been a focal point of how soil management can influence soil water storage (Rawls et al., 2003). Yet, recently, the axiom "more SOM equals more plant available water" has been questioned (Minasny and McBratney, 2018). In general, positive relationships between SOM and plant available water are strongest in soils with lower SOM and coarse textures (Hudson, 1984; Rawls et al., 2003; Villamil et al., 2006; Gupta et al., 2020). Using a large dataset, Minasny and McBratney (2018) reported that the relationship between SOM and plant available water is overall weak, mainly observed near field capacity in sandy soils and negligible in finer soil textures. Similar results have been found in soils from Mediterranean Europe, where higher SOM did not raise plant available water (Bonfante et al., 2020). Higher SOM not translating into higher plant available water could be due to simultaneous increases in water retained at field capacity and permanent wilting point (Renwick et al., 2021).

Soil texture plays a mediating role in the magnitude and direction of soil health practices, namely no-till, continuous living cover, and cover cropping, and their effect on plant available water. Effects of no-till on plant available water were negative in clayey soils, negligible in fine-textured soils with high SOM, and marginally positive in silt loam soils (Kinoshita et al., 2017). Continuous living cover (cover crops, perennial grasses, agroforestry, and managed forestry) showed similarly mixed outcomes on plant available water as with no-till, where no significant effect on plant available water was found for soils containing >25% silt or >30% clay (Basche and DeLonge, 2017). However, for lighter textured soils, a 9.3% increase in water retained at field capacity was found when continuous cover was implemented (Basche and DeLonge, 2017).

Soil health management variably affects soil hydrologic functioning, and more local research is necessary to create regional and site-specific soil health recommendations to improve water provisioning (Devine and O'Geen, 2019). New methods are needed to quantify the partitioning between productive (transpiration) and nonproductive (evaporation) flow, such as assessing the components of the surface energy balance and how varying soil health management practices partition water fluxes into evaporation versus transpiration (O'Brien and Daigh, 2019). Studies are also needed on the potential trade-offs of cover cropping and its effect on the water balance in semiarid regions (Mitchell et al., 2015). For example, some studies have found that both percolation and water storage were reduced under cover cropping (Gabriel et al., 2012; Ward et al., 2012; Mitchell et al., 2015; Meyer et al., 2019), while others show no or little effect (DeVincentis et al., 2022). Several factors will influence outcomes for the water balance, such as the termination timing of the cover crop prior to the cash crop growing season (Alonso-Ayuso et al., 2018), the type of cover crop (or mixture of cover crops; Nielsen and Vigil, 2005), the balance between cover crop transpiration versus improvements to soil physical properties that increase water capture, and then provisioning during the cash crop season and weather (Mitchell et al., 2015; Jones et al., 2020). For instance, cover crops could increase soil moisture after their termination if there is sufficient post-termination rainfall, despite transpiring water during cover crop growth (Unger and Vigil, 1998; Carlson and Stockwell, 2013; Burke et al., 2021). Multiyear studies are needed to identify the local management and weather conditions that favor positive outcomes for water under cover cropping in semiarid regions.

Plant—soil—microbe interactions

Soil health management strongly affects plant–soil–microbe interactions (Dias et al., 2015; Bender et al., 2016; Mariotte et al., 2018) and, as such, impacts the effective use of water. Specifically, practices like conservation tillage, cover cropping, organic matter amendments, and diversification of crops typically enhance microbial biomass relative to conventional practices (Paustian et al., 1997; Kallenbach and Grandy, 2011; Poeplau and Don, 2015; McDaniel et al., 2016) and sometimes increase microbial richness and diversity (Oehl et al., 2004; Bowles et al., 2017; Van Geel et al., 2017; Guzman et al., 2021). Further, soil health management practices impact diversity and density of soil macrofauna, such as earthworms (Ernst and Emmerling, 2009), and positively affect the biological suppression of soil pathogens (Abawi and Widmer, 2000; Larkin, 2015). In turn, these changes can promote productive water use through general impacts of soil microbes on soil structure and biogeochemical processes, as well as through specific plant–microbe interactions (Zheng et al., 2018), particularly those mediated by arbuscular mycorrhizal (AM) fungi and plant growth promoting rhizobacteria (PGPR).

The soil microbial community as a whole has mainly indirect effects on productive green water flow and blue water conservation. By driving nutrient cycling and increasing plant nutrient availability (Williams and Vries, 2020), soil microbes—with the exception of soilborne pathogens—help remove limitations to plant growth and allow plants to take full advantage of available water. Greater plant productivity, specifically increased canopy cover, mediated by plant–soil–microbe interactions further reduces evaporation and increases productive green water flow (Rockström et al., 2009; Nziguheba et al., 2010; Sánchez, 2010). Moreover, soil microbes are critical for soil structure formation: soil microbial decomposition processes drive aggregate formation and aggregate turnover, which dictates soil structure (Six et al., 1999; Rillig and Mummey, 2006). Since soil structure affects soil microbial activity by altering soil water retention (Schjønning et al., 2011; Moreno-Espíndola et al., 2018) and soil management affects both structure and microbial activity, complex feedbacks exist among soil microbial activity, soil structure, soil management, and green and blue water.

AM fungi are ubiquitous root symbionts that require plant carbohydrates and in return benefit their hosts via various mechanisms such as enhanced access to nutrients and water (Smith and Read, 2010). Intensive agricultural management strategies, such as frequent chemical and physical disturbance, alter soil nutrients and crop diversity, effecting AM fungal abundance, diversity, and community composition, specifically the relative abundance of AM fungal functional groups (Oehl et al., 2004; Chagnon et al., 2013; Van Geel et al., 2017; Guzman et al., 2021). Reduced tillage and winter cover cropping increase AM fungi root colonization of annual cash crops by about 30% on average, while reduced tillage can increase richness of AM fungal taxa by 11% (Bowles et al., 2017).

There are both indirect and direct mechanisms through which AM fungi affect productive green water flow and blue water conservation. AM fungi play an important role in enhancing soil structure (Rillig and Mummey, 2006) through extraradical hyphae that physically enmesh aggregates (Mardhiah et al., 2016). AM fungi can enhance plants' drought tolerance by improving access to nutrients and maintaining physiological performance. This, in turn, increases plant growth (Smith and Read, 2010), strengthens plants' ability to recover, and/or prevents severe root and photosynthetic apparatus damage (Augé, 2001). Further, AM fungi affect plant water relations, such as stomatal regulation (Duan et al., 1996; Lazcano et al., 2014; Augé et al., 2015) in ways that may optimize responsiveness to low or variable soil moisture. AM fungi stimulate antioxidant enzyme activity, which alleviates damage caused by reactive oxygen species under drought stress and improves water use efficiency and greater recovery of plants post drought (Pedranzani et al., 2016; Thirkell et al., 2017; Chang et al., 2018; Duc et al., 2018; Li et al., 2019). Lastly, recent findings show that AM fungal hyphae can transport water, but relative to the plants' transpiration demand, the AM fungal-mediated water transfer appears to be low (Püschel et al., 2020). Yet, despite this evidence on how AM fungi influence soils and plant performance during water stress, we still lack a robust understanding of how soil health management can achieve optimized AM functioning with respect to enhancing nutrient and water access to crops in real agricultural settings.

PGPR are root-colonizing bacteria that enhance plants' ability to withstand biotic and abiotic stresses via the production of a wide range of enzymes and metabolites (Mayak et al., 2004; Glick et al., 2007; Kim et al., 2009; Chauhan et al., 2015). Knowledge on the effect of soil health management on PGPR is scarce, but studies suggest PGPR inoculation success may be affected by soil type, temperature, nitrogen content, salt concentration, and moisture content (Adesemoye and Egamberdieva, 2013). PGPR have been shown to enhance plants' ability to tolerate drought stress via various mechanisms (Ngumbi and Kloepper, 2016; Vurukonda et al., 2016; Rubin et al., 2017). PGPR enhances growth promoting and suppresses growth inhibiting phytohormones (Glick et al., 1998; Figueiredo et al., 2008; Belimov et al., 2009; Cohen et al., 2009; Dodd et al., 2010; Bresson et al., 2014) and, hence, increase root growth (Somers et al., 2004; Timmusk et al., 2014) and shoot growth (Vardharajula et al., 2011; Timmusk et al., 2014). Further, relative water content in plants is increased with PGPR, which is important for metabolic activity in plant tissue (Vardharajula et al., 2011; Bano et al., 2013; Grover et al., 2014; Naseem and Bano, 2014; Naveed et al., 2014). Finally, PGPR induces overproduction of antioxidants and thus enhances plants' drought tolerance (Ngumbi and Kloepper, 2016). However, as for AM fungi, work remains to translate the possible effects of PGPR on plant drought tolerance to actionable management information for agricultural systems.

Macrofauna, for example, earthworms and ants also impact soil water dynamics through the galleries and chambers they create and that facilitate enhanced infiltration (Sofo et al., 2020). Further, by redistributing and stabilizing organic matter, macrofauna also contributes to soil aggregation and as such further enhances soil nutrient retention (Fonte et al., 2010; Sofo et al., 2020). Consequently, macrofauna may also improve productive water flow through supporting enhanced plant growth.

Plant water capture and productive use

Soil health management that impacts below- and aboveground plant traits can shift both the plant's ability to access and take up soil water and its transpiration demand. Water movement through the soil–plant–atmosphere continuum is a process driven by water potential gradients and affected by the conductivity or resistance of the pathway, such as soil and root hydraulic conductivity and stomatal conductance (Steudle, 2001). Transpiration generates high water potential gradients through the soil–plant–atmosphere continuum and may increase with greater canopy cover and environmental evaporative demand, a function of air temperature, humidity, radiation, and wind speed. To what extent plant canopies meet this atmospheric evaporative demand varies with root system architecture, depth, root length density, and other root physiological traits such as hydraulic conductivity (Barrios-Masias et al., 2019). It is likely that for many crops, modern breeding and selection mainly for aboveground traits in nutrient and water-rich environments have resulted in smaller root systems unable to explore a larger soil volume, diminishing the capacity of crops to respond to water deficit and increasing the dependency on irrigation (Jackson and Koch, 1997; Bishopp and Lynch, 2015). Irrigation management itself influences roots, such as concentration of roots around subsurface drip irrigation lines, and may interact with crop genotype to promote or hinder root proliferation (Li et al., 2010). Root systems have been understudied, and root system architecture and growth habit are important determinants for water uptake. For instance, a 3-year old plum tree (Prunus persica L.) can occupy 50 m^3 of soil with a root system composed of woody and fine roots, which actively respond to the soil environment (Vercambre et al., 2003), and annual crops tend to increase their resource uptake at deeper soil profiles when reaching maturity (Weaver and Bruner, 1928). Thus, understanding root proliferation and its plasticity in a heterogeneous soil profile, including abiotic and biotic interactions as influenced by soil health management, could result in more effective use of water.

Soil health management can create conditions favorable to root growth, such as increasing soil macroporosity, reducing penetration resistance, and maintaining soil moisture, which facilitate root elongation, oxygen diffusivity, and heat transport (Nunes et al., 2019). A generalized framework across management practices is that higher SOM due to soil health management tends to increase aggregation and promote growth and maintenance of roots by alleviating negative impacts from both compaction in drying soils and poor aeration in waterlogged soils (King et al., 2020). Soil health management practices that include deep-rooted crops and continuous living soil cover for most of the year, such as cover crops, perennial forage, and grain crops, can further alleviate negative impacts of compaction by creating root channels, or biopores, that subsequent crop roots use at lower metabolic cost to the plant (McCallum et al., 2004; Williams and Weil, 2004; Perkons et al., 2014; E. Han et al., 2015). SOM derived from living roots in soils is more efficiently stabilized by microbes and more persistent in soil than the inputs of shoot residues (Kong and Six, 2010). This may create positive feedbacks over years to decades between greater root growth, belowground carbon input, SOM accrual, microbial activity, and improved soil aggregation and hydraulic properties (see previous sections) (Austin et al., 2017). Trade-offs for soil health management practices must be considered. For instance, no-till practices can reduce root penetration in the topsoil even as it alleviates subsoil compaction (Munkholm et al., 2013) and negatively impact root architecture and growth of the main root axes (taproot), limiting the capacity for root exploration and water uptake (Martínez et al., 2008).

Root interactions with rhizosphere microbial communities, particularly AM fungi, may impact not only root water and nutrient access and uptake but also potentially root-to-shoot signaling that influences canopy plant–water relations and helps maintain canopy transpiration in drying soils (see previous section on plant–soil–microbe interactions). Root traits that favor desirable root–microbe interactions may have been lost during selection for increased yields under high input systems, which hinders the positive effect of increased soil health (Schmidt and Gaudin, 2017; Barrios-Masias et al., 2019). Intensive agricultural systems tend to select for high-yielding crops, without regard for robust root systems and soil–plant communities (Pretty and Bharucha, 2014). Selecting adaptive root responses to water availability by breeding has rarely been applied to irrigated systems (Schmidt and Gaudin, 2017).

Soil health practices such as crop rotation diversification and organic management favor disease-suppressive and pest-suppressive soils and facilitate rhizosphere soil–microbe–plant interactions, which could help limit yield reductions due to pests and disease (Peralta et al., 2018; Blundell et al., 2020). Soil health management also boosts nutrient cycling by soil microbes and nutrient availability to plants, including nitrogen, which has been shown to improve the water use efficiency of crops, such as wheat under low water availability (Cousins et al., 2020; see previous section on plant–soil–microbe interactions). Higher soil biological health has been shown to increase maize yield even in intensively managed systems (Wade et al., 2020). If soil health management alleviates yield-limiting factors and thus increases crop growth and canopy cover (e.g., percent soil canopy cover), it may increase productive water flow.

Leveraging soil health benefits in irrigated systems

Soil health and water conservation in irrigated systems

Shifting irrigation strategies is essential to realizing potential benefits of building healthy soils for blue water conservation in irrigated cropping systems, especially when blue water is a substantial portion of the crop water budget. If soil health management results in capturing and storing more green water, but managers do not reduce blue water inputs, then greater blue water conservation will not be achieved. Similarly, storage of green water may not be utilized by a crop if the root system cannot access it (e.g., shallow rooted crops). Since irrigation managers must recognize and react to changes in soil health that affect water dynamics in order to conserve blue water, realizing the full benefits of soil health management is more complex in irrigated systems compared to rainfed systems that only rely on green water. We consider how several irrigation strategies could interact with healthy soils to support water conservation and reduce vulnerability to droughts or policy interventions that impact blue water supplies, an approach which we call "integrated soil health-water management," revealing many research gaps (**Table 1**). We focus on regions with Mediterranean-type climates that have distinct wet and dry seasons (e.g., California, Chile, Mediterranean Europe/North Africa, the Middle East, and parts of Western and South Australia).

First, increasing the proportion of precipitation captured and stored as green water during the rainy season could allow for a delay in the onset of irrigation, in turn saving blue water (Devine and O'Geen, 2019). Irrigation can be delayed until just before the onset of plant water stress, which broadly speaking occurs when about half of plant available water in the soil has been consumed, a proportion known as allowable depletion (Hanson et al., 2000; Devine and O'Geen, 2019). For instance, in California, processing tomato fields may not be irrigated for the initial 2–3 weeks after transplanting in early spring as seedlings establish with stored green water. Increasing the quantity of plant available water and delaying irrigation initiation would allow for stored green water to contribute relatively more to the crop water budget. Roots would also grow more deeply if seedlings are not established with abundant surface water.

Reducing nonproductive evaporative losses of water (green or blue) and/or increasing green water capture could also result in less irrigation water applied. When irrigation is applied on the surface or overhead, substantial reductions in evaporation result from reduced tillage and residue retention (Klocke et al., 2009; Peng et al., 2020). For instance, wheat production under semiarid conditions under no-till and mulching increased yields by over 40% and precipitation use efficiency by at least 39% (Peng et al., 2020). In tomatoes, no-till and residue retention resulted in an estimated 5–10 cm of reduced evaporation in California annual cropping systems (Mitchell et al., 2012), which accounts for approximately 10% of crop ET. Since residues also reduce surface runoff (Smith, 2016), they can enable less frequent, deeper irrigations, which maximize benefits of reduced evaporation (Mitchell et al., 2012). Cover crops are highly effective at increasing infiltration of winter rainfall and could act in concert with soil management that increases soil water storage to increase overall green water availability for crops. Yet, perception that cover crops can result in a net reduction in water availability for cash crops is a key barrier to cover crop adoption in arid environments (Carlisle, 2016). Net impacts of cover crops in irrigated systems must be carefully considered, that is, the balance between increasing the capture of precipitation via increased infiltration and reductions in evaporation versus increases in transpiration and reduction in percolation (Meyer et al., 2019). Careful management for the timing of establishment, termination, and species selection is key to realizing net benefits. In areas with very low winter rainfall, crop residues are an alternative to cover crops for increasing infiltration and reducing evaporation, since there is no risk of competition with cash crops for stored green water (Downer and Hodel, 2001; Iqbal et al., 2019). However, unlike cover crops, crop residues would not increase infiltration at depth or leave beneficial biopores (see the following).

In Mediterranean-type systems with a long dry season, increasing green water capture and storage through soil health management may only be able to play a relatively minor role in reducing irrigation needs. This is because the soil profile can only store so much water and it can be rapidly depleted after rains stop and ET increases dramatically, especially in shallow-rooted crops. In such areas, we suggest that other potential benefits of healthy soils may be similarly or relatively more important for enabling irrigation management that conserves water. First, if soil

Table 1. Irrigation water management strategies and how they interact with soil health management to decrease the use of blue water, increase green water availability, and/or increase the productive flow of water, that is, integrate soil health-irrigation management

Water Management Strategy	Interaction With Soil Health Management	Key Research Questions
Delaying onset of irrigation until a benchmark level of allowable depletion has occurred (Zhang et al., 2021)	Depends on increases in green water availability via greater soil water capture and storage	What are levels of allowable soil water depletion for specific crops? How would delaying onset of irrigation affect direct seeded or transplanted annuals?
Applying fewer, deeper irrigations with reduced total water applied (Waqas et al., 2021)	Reducing evaporation and increasing rainfall infiltration by cover cropping, crop residues, mulching, and/or no-till results in less blue water needed to meet crop water demand	How can cover crops be managed across varying agro-climatic contexts to optimize impacts on soil water content for subsequent cash crops? Could this be implemented with drip irrigation systems?
Deficit irrigation or partial root-zone drying (Barrios-Masias and Jackson, 2016; Lipan et al., 2019)	Greater plant–microbe interactions and root proliferation and penetration could reduce impacts on crop production	To what extent will soil health management maintain or enhance crop productivity from varying levels and approaches to deficit irrigation or partial root zone drying?
Matching irrigation strategy with root system traits (García-Tejera et al., 2018; Vincent et al., 2020)	Root proliferation in well-structured topsoil could maximize capture of shallow irrigation while deep root penetration could maximize deep stored water from higher infiltration	Is the root system architecture of crops and varieties suited to access stored soil water at different depths? How could breeding programs help match crops with patterns of water availability?
Adaptively design cropping patterns to optimize water use (Chen et al., 2022)	Planning and adaptively managing crop rotations, fallowing, and/or intercropping to facilitate complementariness in water use in space and time could enhance green water availability	How could interspecific interactions in intercropping enhance water use efficiency? Do crop rotations based on rooting depth differences increase the efficient use of stored water?
Managed groundwater recharge (Meyer et al., 2019)	Cover cropping could facilitate groundwater recharge by maintaining soil structure and reducing nutrient loading to groundwater	How does the timing of flood flow applications and cover crop establishment interact to affect nutrient retention and deep percolation? When should a cover crop be terminated to reduce nonproductive water flow?
Irrigation efficiency technologies (Dumont et al., 2013)	Smaller, more frequent, and more localized irrigation could reduce other benefits from soil health improvements if only a very small portion of the soil profile is moist during the growing season	How can effective water governance policies be designed to minimize the potential for Jevon's paradox due to increases in water use efficiency at the field scale? What are the trade-offs between irrigation technologies and soil health benefits based on water distribution in the soil profile?

health management promotes plant–microbe interactions and greater root proliferation/penetration, then it may be possible to use various irrigation strategies, such as deficit and partial root zone drying (**Box 1**; Barrios-Masias and Jackson, 2016) that reduce blue water consumption while minimizing impacts on crop productivity. Soil health management that enables deficit irrigation may be particularly important in perennial crops (e.g., nut trees) that require significant capital investment to establish and cannot be fallowed during times of water scarcity. Composted manure application in an almond orchard in California increased soil volumetric water content in the top 1.5 m by 22% during the driest part of the study year (Lepsch et al., 2019), suggesting organic matter-building strategies could be used to reduce the impacts of deficit irrigation on tree water status.

Soil health management could also help different types of root systems adapt to irrigation management and improve the effective use of water. With irrigation, crops often invest preferentially in shallow roots, especially with drip or microsprinkler systems in which applied water is more localized and does not penetrate deeply into the soil profile (Li et al., 2020). Well-structured soils with low resistance to root proliferation could help crops rapidly develop shallow axial roots with extensive lateral branching that would enable exploitation of water and nutrient

Box 1. Irrigation management strategies to reduce blue water inputs

Deficit irrigation implies reductions in the amount of water provided to a crop compared to a fully irrigated crop based on the total crop evapotranspiration (ET). A fully irrigated crop would receive blue water equivalent to crop ET. Two approaches for reducing the amount of blue water applied are a controlled deficit irrigation and partial root zone drying. The former is applied during certain crop stages when drought has less impact on yield (e.g., fruit ripening in tomatoes). Partial root zone drying integrates plant physiological responses to drought (e.g., tighter regulation of transpiration rates) by wetting only part of the root system (e.g., 50%), which is alternated in each irrigation. Partial root zone drying can be applied during most of the growing season. However, not all crops or cultivars may respond well to these irrigation strategies.

resources concentrated near the soil surface (Schmidt and Gaudin, 2017). Yet, this could also limit root access to water (and nutrients) available deeper in the full soil profile (Barrios-Masias et al., 2019). Biopores, such as those formed from roots or earthworms and preserved when soil is not disturbed, enable steeper-angled axial roots to penetrate deeper (Stirzaker et al., 2017; Xiong et al., 2022). Selection of cover crops or preceding cash crops that promote biopores helps subsequent cash crops develop deeper roots (Huang et al., 2020; Zhang et al., 2022). In turn, this would support reducing applied water, such as through partial root drying (Barrios-Masias and Jackson, 2016) or with less frequent irrigations at drier soil moisture thresholds (Devine and O'Geen, 2019). With careful crop and cultivar selection, promoting deep rooted crops can allow for more consistent access to soil moisture without a rapid onset of drought stress and even allow for dry farming (Leap et al., 2017; Garrett, 2019), a strategy involving almost complete reliance on green water during seasons without rainfall and long practiced by desert farmers and Indigenous peoples around the world (Nabhan and McKibben, 2013).

Over larger areas and longer timescales, managing groundwater recharge through enhanced percolation will also be essential to "bank" water available during wet years for drier years. As finite surface water allocations decline in the future, demands on groundwater will continue to increase (Massoud et al., 2018). Could building soil health improve regional water balances by enhancing deep percolation? In California, groundwater overdraft has occurred at a rate of 2.5 billion cubic meter per year since 1960 due to pumping for irrigation and increased reliance on groundwater during times of drought (Public Policy Institute of California, 2018). Recognizing the potential for depleted aquifers to store 44–80 km^3 of water, or 3 times that of surface water reservoirs, the state's water managers have accelerated the pursuit of managed aquifer recharge on working landscapes, including croplands (Dahlke et al., 2018). In years with high-magnitude streamflows, above the required environmental flows and surface water allocations, excess water can be diverted onto agricultural fields to recharge underlying aquifers (Kocis and Dahlke, 2017). A field site's ability to quickly infiltrate and accommodate deep percolation of water below the root zone to groundwater is essential for increasing the recharge capacity of a site and to avoid negative effects on perennial crop physiology (O'Geen et al., 2015). While areas suitable for groundwater recharge are mainly influenced by subsurface soil properties, topography, and crop type (O'Geen et al., 2015), soil health management could help increase percolation below the root zone and reduce potential negative consequences of aquifer recharge. For instance, nitrate pollution of groundwater could occur if significant residual nitrate exists in the soil profile, exacerbating pollution that has already contaminated drinking water wells in many areas of California (Balazs et al., 2011; Bastani and Harter, 2019; Waterhouse et al., 2020). Cover crops could help reduce nitrate levels while also increasing infiltration during managed aquifer recharge.

Trade-offs and contradictions with irrigation efficiency technologies

Irrigation technologies that increase crop yield per unit of water applied can also reduce pressure on blue water resources. Subsurface drip irrigation, soil water monitoring, and other efficiency technologies can lead to significant reductions in water applied with similar or higher levels of productivity.

When benefits outweigh the capital investments required, irrigation efficiency technologies spread rapidly, such as the widespread shift from furrow irrigation to drip and microsprinkler irrigation in California (Taylor and Zilberman, 2017). Yet, trade-offs also must be considered. For instance, subsurface drip irrigation reduces percolation during the summer when irrigation occurs, limiting the ability to store water during wet years when surface water is more abundant (Perry, 2007; O'Geen et al., 2015; Scanlon et al., 2015; Niswonger et al., 2017). Another major issue occurs when increases in irrigation efficiency at the field scale lead to expansion of irrigated acreage or higher value but more water-intensive crops, thus actually increasing total blue water use at the regional scale (Alcott, 2005; Sears et al., 2018). This is one example of a widely recognized environmental challenge, called Jevon's paradox, that limits the utility of interventions aimed at increasing resource use efficiency at a small scale without effective governance and policies at broader scales.

There are also possible trade-offs with soil health. In a comparison of furrow irrigation, which wets a greater volume of soil less frequently, and subsurface drip irrigation, which wets a smaller volume of soil more frequently, Schmidt et al. (2018) found that subsurface drip reduced the soil's C sequestration potential. Specifically, furrow irrigation had larger soil aggregates in the upper 10 cm of the soil, a greater proportion of C in macroaggregates, and a lower proportion of C in the unprotected silt and clay fraction compared to subsurface drip irrigation after just 2 years. While the drip system had higher blue water productivity (i.e., more crop per drop) than furrow, declining aggregation in the drip irrigated system could affect infiltration and percolation during the rainy season and thus potentially green water storage and blue water recharge (Schmidt et al., 2018). Different soil wetting patterns with subsurface drip irrigation also affect soil bacterial and fungal community composition, though functional implications are not clear (Quach et al., 2022). While limited research exists currently, these studies suggest that different wetting patterns of subsurface drip or microsprinklers may impact soil health.

Transitions to integrated soil health-water management

Developing strategies for integrated soil health and water management and quantifying outcomes are important steps to leverage more green water and reduce applied irrigation water, toward a larger goal of sustainable water resource management in irrigated regions. But such knowledge will not be sufficient to actually make the shift (Chartzoulakis and Bertaki, 2015; Iwanaga et al., 2020). With changes in decision-making required across multiple, interacting levels, from individual farms to irrigation water management districts to regional policymaking, driving transitions in both soil health systems and water resources management is complex and social–ecological in nature. For example, structural factors like the degree of land tenure, access to values-based markets, and public and private policy all influence farmers' adoption of soil health practices (Carlisle, 2016; Carlisle et al., 2022), with motivation and other personal characteristics playing an important mediating role. Shifting to various deficit irrigation management strategies or less water-intensive alternative crops will likely be by necessity only, such as when water for irrigation is less available and/or becomes more expensive (Trout and Manning, 2019). Deficit irrigation involves more risks for crop productivity, and alternative crops may generate lower returns, which is an issue when the highest value cropping systems in a region drive land values. While some exceptions exist, such as when deficit irrigation leads to profitable increases in crop quality despite lower yields (e.g., with dry farmed tomatoes or wine grapes; Acevedo-Opazo et al., 2010), motivation to reduce water inputs will need hard climate or regulatory realities. Yet, such realities may actually be a window of opportunity for farmers to try soil health management as a strategy for reducing the negative impacts of less water available. Times of crisis can spur farmers to reevaluate their systems, consider new possibilities, and experiment in novel ways (Folke et al., 2010; Darnhofer, 2014). Innovations could spread when farmers who pioneer integration of soil health and irrigation management and find new ways of thriving with reduced blue water availability share their experiences and knowledge through farmer-to-farmer networks.

At broader levels, policies must address common pool resource problems (Ostrom, 1990) or problems in which action at the individual level does not produce optimal outcomes for all users. Participatory policy processes are essential not only to consider the wide array of values, knowledge, and perspectives that farmers, water managers, and other stakeholders bring but also to increase the scope of possible solutions and generate momentum for collective action (von Korff et al., 2012). As an example, groundwater use in California has resulted in a quintessential common pool resource problem and extreme levels of groundwater overdraft (Faunt et al., 2016). To address this, in 2014, the California legislature enacted the Sustainable Groundwater Management Act (SGMA), which established new basin-level management institutions, Groundwater Sustainability Agencies (GSA), tasked with developing locally relevant Groundwater Sustainability Plans (GSPs). As a form of collaborative governance, SGMA mandates that all interested water users, and specifically disadvantaged communities, be involved in the process (Lubell et al., 2020). GSPs must chart how the basin will achieve groundwater sustainability via several approaches, including voluntary, incentive-based water saving approaches, implementing on farm managed aquifer recharge, and control policies such as implementing pumping quotas (Niles and Hammond Wagner, 2019). Pumping quotas could result in fallowed fields and negative consequences for the agricultural industry. If incentive programs for soil health management were coupled with regulations for water resources like SGMA, then some negative impacts could be avoided. In other words, providing support for soil health practices could also help farmers adapt to regulatory and climate realities of water limitations. Following the California example, the state-level Healthy Soils Program (HSP) currently provides grants for soil health practices and recognizes the many cobenefits of building soil health (California Department of Food and Agriculture, 2022), but synergies between HSP and SGMA remain undeveloped. GSAs could engage with technical assistance providers to support farmers' transitions to soil health management in concert with water-saving irrigation practices (**Table 1**), building on lessons learned from pioneering farmers, much like a regional model for developing conservative agriculture (Mitchell et al., 2016). In turn, modelers could quantify how integrated soil health and water management at the field scale affects the regional water balance. For example, could adoption of soil health practices and changes in irrigation strategies, such as deficit irrigation or changes in the timing and duration of irrigation events (**Table 1**), if broadly incentivized and adopted, be impactful components of GSA GSPs? How could building soil health on low permeability soils improve infiltration and a farmer's ability to participate in managed aquifer recharge programs, expanding beyond only sites with soils already capable of high infiltration rates (O'Geen et al., 2015)? In sum, regulatory intervention and governance are necessary to move water resource use toward sustainability, while incentives and technical assistance for soil health management could help farmers adapt to new realities with fewer negative consequences. Doing so will require the active commitment and collaboration of farmers, policymakers, and other stakeholders.

Quantifying outcomes: Opportunities and knowledge gaps

Water resource managers, farmers, and other stakeholders require quantitative information on the potentials and limits of integrated soil health-water management to increase productive green water flows, resilience to blue water shortages, and conservation or even regeneration of blue water resources. Most reports on soil health response to management quantify soil physical, chemical, and more rarely, biological indicators of soil health, as we have reviewed here. While such approaches are crucial for establishing linkages between management and these dynamic properties, understanding the impact of such changes on plant-water relations, crop productivity during drought or deficit irrigation, or on green and blue water flows at scales beyond the plot or field is much more challenging. To move beyond optimistic guesses to actionable information, research and development in several areas are needed.

Rather than focus mainly on soil health indicators, field-scale trials must be able to demonstrate the outcomes of soil health management for hydrological processes, plant water status, crop production during water limitation, and blue water savings. Doing so may require new experimental approaches (Gilbert and Medina, 2016). For instance, recent field trials have linked organic matter additions in the form of compost and chipped woody biomass to higher soil moisture and measurable mitigation of tree water stress including under deficit irrigation (Lepsch et al., 2019; Jahanzad et al., 2020). When possible, we recommend experimental designs with a gradient of irrigation water inputs, such as 25%, 50%, 75%, and 100% of crop ET, to determine whether thresholds in terms of crop stress or yield response to deficit irrigation differ between soil health management treatments and controls. However, standardizing irrigation volume in soil health treatments and controls limits inference about mechanisms other than higher soil moisture. Rather than standardizing by irrigation volume, standardizing soil moisture between soil health treatments and controls would allow testing for soil health management-induced shifts in dynamic soil biological and physical properties, plant–soil–microbe interactions, root water acquisition, and plant water status, rather than only soil moisture per se. For example, a deficit irrigation experiment with no difference in soil moisture between treatments with and without symbiosis with AM fungi showed that AM fungi alleviate plant water stress under deficit irrigation when soil moisture is similar between treatments with and without AM symbiosis (Bowles et al., 2016). Soil sampling or preferably soil sensors that are used for irrigation management could monitor soil moisture in a treatment or experimental unit and then variable irrigation volumes could be applied to standardize soil moisture between soil health treatments and controls. Another option that could be more feasible than standardizing by soil moisture, and helps avoid challenges of soil heterogeneity and sensor measurement area, is standardizing by plant water status through direct measurement or proximal or remote sensing at the plant, plot, or field scale, which would allow the blue water savings that are hypothetically possible through soil health management to be quantified, regardless of whether higher soil moisture, plant water status, or other mechanisms are responsible. Future manipulative and observational studies could generate insight into the relative importance of key pathways (abiotic and biotic paths) through which soil health management protects plants in water-limited conditions, such as impacts on the soil water balance, soil nutrient cycling, and plant water and nutrient uptake and status with or without the contribution of soil microbes, and target management accordingly.

In regions with irrigated landscapes and large water conveyance systems, scaling up the impacts of soil health management beyond the plot or field scale is essential to quantify potential blue water conservation through increasing green water availability, irrigation savings, and/or aquifer recharge. Quantification is essential for assessing the relative costs and benefits of different interventions (Hoekstra, 2019). For example, in California, approximately 3.5 M ha of irrigated croplands consume 36–46 km^3 of blue water annually (Cooley, 2020). Yet, the availability of surface water resources is increasingly volatile as climate change progresses, leading to groundwater overuse and subsequent policies to implement state-mandated GSPs (Harter, 2015). Given the uncertainty in surface water availability, reduced pumping likely will have to be included in GSPs to bring groundwater basins back into sustainable use (Escriva-Bou et al., 2020). In an analysis by Devine and O'Geen (2019) based on inherent soil properties, deficit irrigation (down to 1 m deep and 50% allowable depletion) in perennial cropland across California could produce blue water savings equal to 30 km^3 and increase green water use by 7 km^3 over 13 years. This is equivalent to filling the largest surface reservoir in the state, Shasta Lake, 6.6 times over.

To what extent could adoption of soil health management increase green water availability and reduce demand for blue water for irrigation? Would incentivizing adoption of such practices at scale be more cost effective than alternatives like increasing surface reservoir capacity and with more cobenefits? To what extent could soil health management also increase aquifer recharge through enhanced percolation or reduced groundwater withdrawals, thus forming part of GSPs in California or analogous policies elsewhere? Such questions will require interdisciplinary research that supports agro-hydrological modeling across scales. We identify several challenge areas where modeling development is needed.

Capturing agroecosystem changes due to soil health by modeling

The answer to the key question of how building healthy soils impacts the use of water resources in irrigated agriculture depends on interactions among multiple spatial and temporal scales, and ultimately on water resources management itself. For instance, at the plant canopy to field scale, models must be able to capture how agricultural management, including practices to increase soil

Table 2. Model summary of selected models used in the comparison of both soil health management and green-blue water balance

Model	Model Type	Focal Scale	"Less Drop per Crop" and "More Crop per Drop" Examples Related to Soil Health and Green-Blue Water Balance
Lund-Potsdam-Jena managed Land	Process based	Global	– Effects of tillage in crop productivity (Lutz et al., 2019) – Mulching and conservation tillage in irrigated systems (Jägermeyr et al., 2016) – Combined effect of reservoir operation and irrigation extractions (Biemans et al., 2011)
Soil & Water Assessment Tool	Physical based	Hydrologic and erosion model at the basin scale	– Importance of capillary rise (Kroes et al., 2017) – Irrigation and reservoir storage (Jouma and Dadaser-Celik, 2021) – Crop yield and irrigation optimization (Sun and Ren, 2014)
AquaCrop	Process based	Crop simulation at field scale	– Irrigation and capillary rise in crop productivity (Khan et al., 2021) – Deficit irrigation and mulching in crop productivity and water savings (Bao, 2020) – Water saving effect of mulching and drip irrigation (Nouri et al., 2019b)
HYDRUS 1D	Physical based	Water flow and solute transport through the soil profile	– HYDRUS-1D coupled with a crop growth model: impact of groundwater in productivity (M. Han et al., 2015) – Water dynamics in irrigated conservation agriculture (Bekele et al., 2020) – Water balance under no tillage and soil organic matter incorporation (Aggarwal et al., 2017)

health and irrigation, affects soil hydraulic properties and hydrologic flows. Beyond the field, at a basin scale, hydrologic and water resource models must be able to capture how these changes in turn affect green and blue water flows and reservoirs. For instance, changes in infiltration and soil water storage at the field scale could affect runoff and percolation, and thereby blue water flows to surface and groundwater (Flint et al., 2013; Lei et al., 2021). Such coupled models could in turn be used to assess different climate change scenarios, including drought, and reduced blue water supply.

Recent work has focused on how to capture the effect of soil health practices in hydrologic models (Maharjan et al., 2018; Evenson et al., 2022). With this work as a -starting point, we selected 4 representative and widely used models that simulate the movement of water at different scales. We highlight strengths, weaknesses, and opportunities for capturing the impacts of soil health management on green and blue water flows (**Table 2**). We consider both approaches for estimation of water savings: less drop per crop (water management strategies) or more crop per drop (closing yield gap at constant water use) (Blum, 2009; Bao, 2020).

At the global scale, the Lund-Potsdam-Jena managed Land (LPJmL; Rost et al., 2008) model evaluates global blue-green water patterns. LPJmL is a dynamic global vegetation and hydrologic model, which models coupled carbon, nitrogen, and water fluxes, crop growth and yields. Improvements to LPJmL, including irrigation schemes (Rost et al., 2008) and reservoir management, assess the changing role of reservoirs in sustaining water supply for irrigation in agroecosystems (Biemans et al., 2011). Additionally, LPJmL 5.0 takes into account the impacts of tillage by focusing on changes in SOM pools and bulk density (Lutz et al., 2019), making LPJmL potentially capable of assessing how tillage affects irrigation demand and crop yields.

At a watershed to basin scale, the Soil & Water Assessment Tool (SWAT; Arnold et al., 1998) model predicts the impacts of land management practices on water and sediment flow, including crop yield and crop water productivity, and can incorporate irrigation scheduling (Sun and Ren, 2014). The SWAT model has been used to estimate green and blue consumption at basin scale, allowing efficient water and soil management (Msigwa et al., 2022). However, SWAT cannot estimate water losses to evaporation from water reservoirs, channels, and after irrigation water application (Luan et al., 2018), limiting blue water flows estimation. SWAT becomes inaccurate at modeling streamflow during drought periods (Veettil and Mishra, 2016), a disadvantage in running climate change scenarios. However, a calibrated SWAT version was developed validating input parameters for wet and dry seasons (Zhang et al., 2015).

At the field scale, the Food and Agriculture Organization model AquaCrop estimates green-blue water balance and plant growth and can incorporate management impacts on blue water, such as using drip irrigation and soil management techniques like mulching (Chukalla et al., 2015; Nouri et al., 2019b). Currently, AquaCrop does not simulate lateral water flows, fertilization, or nutrient dynamics (Chukalla et al., 2015). AquaCrop describes soil water stress in more detail than SWAT, but SWAT is more detailed for soil fertilization (Van Gaelen, 2016). AquaCrop may perform better for soil water balance and crop growth processes than SWAT (Hunink et al., 2011) and is better able to parameterize irrigation management. In the comparison of these two models, if "less drop per crop" (decreasing water use at stable yield) is more important than "more crop per drop" (closing yield gap at constant water use), AquaCrop would be more suitable.

In contrast to larger scale models, physical models focused on finer scales like HYDRUS 1D (Šimůnek and Genuchten, 2008) better capture soil hydraulic properties. Capturing how soil health management affects soil hydraulic parameters in process-based models is one limitation in accurately estimating water resources across scales (Dang et al., 2020). For instance, while LPJmL, AquaCrop, and SWAT use total porosity as an input of a unimodal pore size distribution, HYDRUS 1D accounts for dual-porosity, that is, interaggregate pores and intra-aggregate pores with contrasting sizes and hysteresis in the water flow calculation (Šimůnek et al., 2016). Not considering bimodality in topsoils due to soil management derived from tillage may compromise the accuracy of soil-water modeling (Jensen et al., 2019; Acevedo et al., 2020). A HYDRUS 1D module can incorporate the effect of tillage, homogenizing the soil water content and liquid phase concentration in the topsoil layers, although it does not incorporate changes in soil hydraulic properties with tillage (Mallmann et al., 2014).

To realistically capture outcomes for water provisioning, agro-hydrological models must be able to—directly or indirectly via connection to another model—simulate how soil health management affects the dynamic soil properties that influence hydrologic processes and hydraulic properties, shifts in plant growth that influence water access and demand, and eventually, plant–microbe interactions that influence plant responses to water stress. Overall, the agro-hydrological models reviewed here incorporating soil health management have largely focused on reduced or no tillage. Using field data to validate model parameters, other soil health management, such as cover crops or organic matter amendments, could be directly incorporated or, as a starting point, represented through their impacts on SOM. Realistic representation of soil health management and soil-water processes in hydrological models requires targeted data collection and validation for dynamic soil property inputs (Gómez et al., 2020). SOM dynamics are some of the most important soil health management-induced changes in agroecosystems (Bolinder et al., 2020), and accurate modeling of hydrological outcomes of soil health management thus requires comprehensive integration of SOM processes over time (Kemanian et al., 2011). In LPJmL5, all organic matter pools (vegetation, litter, and soil) are subject to decomposition. The decay of organic residues cannot be simulated by standard versions of AquaCrop, HYDRUS-1D, or SWAT, but all of these have been coupled to submodels to address this need. In models where SOM pools are subject to decomposition, hydraulic parameters can be dynamically estimated at different depths based on pedotransfer functions (PTFs) using SOM as an input (Lutz et al., 2019), allowing modeling of soil health practices that affect SOM.

Accurate data on soil physical properties can lead to a better understanding of the state of soil health at local and landscape scales (Keesstra et al., 2021), but some assumptions about soil hydraulic properties can oversimplify their effect on models. First, most hydrological models assume that soil hydraulic properties are constant over time, hampering efforts to capture how management practices temporally affect key properties, such as soil structure and pore size distribution (Chandrasekhar et al., 2019). For example, soil health management can boost pore connectivity (Galdos et al., 2019); however, temporal changes in soil structure are still in early stages of development (Vereecken et al., 2016; Chandrasekhar et al., 2019). Second, another assumption is that at different starting soil conditions, properties are arbitrarily changed after management, commonly as correction factors. An example is the bulk density after tillage. The intensity and type of tillage can be represented in simulation models as a mixing efficiency parameter (mE, from 0 to 1) corresponding to the fraction of change in bulk density after tillage (White et al., 2010). Third, most process-based models that use PTFs, which establish an empirical relationship between easily measurable properties and soil hydraulic parameters, may be a source of uncertainty in the estimation of agroecosystem changes due to soil health. AquaCrop, SWAT, and LPJmL 5.0 use the Saxton and Rawls's (2006) PTF for water characteristics for water potential and hydraulic conductivity by default and HYDRUS-1D uses Rosetta, both developed with U.S. soil databases. This could bias models toward soil types and climate conditions found in this geographic area. Management-induced changes in soil hydraulic properties are also not necessarily consistent across different locations, soils, and experiment designs (Schwen et al., 2011), hampering the use of default parameters in accurate modeling runs. PTF can aid in quantifying the benefits of soil management and can be used to model the effect of changes in management on drought resilience (Bagnall et al., 2022). As Cueff et al. (2021) found, available PTFs applied equally to soils under conservation or conventional agriculture have shown poor accuracy results.

Green water is stored in the Vadose zone, which is the subsurface unsaturated zone between the topsoil surface and the saturated zone below the water table. Modeling unsaturated soil flow properly is thus mandatory for estimating green water use and storage. Favorable soil properties related to water flow in unsaturated, drying soil, including high porosity and a higher fraction of large capillary pores and a lower fraction of gravitational pores

(Kodešová et al., 2009), should be incorporated ideally using real measurements. For example, Maharjan et al. (2018) reviewed 16 hydrological models able to integrate tillage effects and concluded that simulating this management requires site-specific empirical measurement of changes in bulk density after tillage. Notably, hydraulic conductivity at varying water contents is not commonly reported in soil health management studies, which tend to focus on soil physical properties that are relatively easily measurable, such as infiltration or saturated hydraulic conductivity.

Agro-hydrological models could better incorporate and enhance flexibility regarding the biotic components of the soil environment. Across agro-hydrological models generally, the changes in the root zone by crops (and/or cover crops) must be properly represented to calculate ET accurately. HYDRUS-1D can simulate crop growth status and water uptake by plants (Šimůnek et al., 2016; Karandish and Šimůnek, 2019), but the root system is considered as a static component (without feedback between the root system and the soil conditions), limiting ability to simulate agroecosystems under different soil health management practices (Parihar et al., 2019). Largely due to a lack of data and uncertainty about representation in models, hydrologic and crop models do not currently explicitly account for soil biology impacts on plant water uptake, status, and transpiration. Quantifying the effect of soil–plant–microbe interactions on model-relevant inputs such as actual ET would enable their incorporation into models and, ultimately, more accurate estimation of the outcomes of building soil health not only for soil physical properties but also crop resilience under various climate change and irrigation scenarios.

However, models must be simple to ensure their operability. Thus, the challenge to integrate soil health into agroecosystem and landscape hydrology increases the need for calibration data and coupled models. For example, AquaCrop has been coupled to HYDRUS-1D and 2D to describe water flow and retention within the soil profile to validate optimum management practices for increased water storage capacity (Gómez et al., 2020). In a similar approach, HYDRUS-1D has been coupled with SWAT for quantifying the capillary rise from groundwater contribution to crop transpiration (M. Han et al., 2015). To sum up, none of the reviewed models can alone incorporate interactions between soil health and irrigation management and then impacts on green water and blue water reservoirs. Additional development will be needed to incorporate soil health into agroecosystem and landscape hydrology at different scales.

Our analysis indicates that current knowledge of soil health and water is robust on soil moisture, infiltration, and retention (Morris and Bucini, 2016), but to the best of our knowledge, it does not yet capture soil health's effect on whole-system hydrologic functioning via modeling. Modeling is a promising avenue for quantifying the magnitude of soil health-induced gains in water savings and drought resilience in irrigated agricultural landscapes. However, current models neither capture the full effect of soil health practices on soil hydraulic parameters nor the influence of soil, plant, and microbial processes and interactions on water cycling.

Conclusions

We show several pathways through which soil health management could synergize with irrigation and crop management to increase the effective use of green and blue water resources in irrigated cropping systems. Widely cited benefits of soil health management in rainfed agriculture, namely, higher infiltration rates and soil water storage, are an important way to increase green water availability. Yet, greater beneficial plant–microbe interactions, root water capture, and reducing plant water stress are at least as important for maintaining productivity in irrigated contexts that depend more on blue water than green water, especially in Mediterranean climate regions dominated by perennial crops that cannot be fallowed during periods of water scarcity. We provide a road map for how soil health management can enhance the effectiveness and suitability of irrigation and water resource management strategies that conserve water resources, such as deficit irrigation or agricultural managed aquifer recharge, and related uncertainties and challenges yet to be resolved. Future research priorities include: (1) promising agro-hydrological modeling strategies and gaps for quantitative scenario analysis and (2) planning to discern possible gains in water conservation and drought resilience through integrated soil health-water management. Impacts on water resources, especially increases in aquifer recharge through enhanced percolation or reduced groundwater withdrawals, are important to evaluate. For quantitative information on how soil health management affects water resources at scales relevant to water resource managers, soil, crop, and hydrological models must be better integrated and expanded, including potential physical and biological changes in the soil. Challenges, trade-offs, and unintended consequences of soil health management for water conservation are also possible, for instance, if blue water conservation through soil health management at the field scale enables expansion of irrigated acreage. Changes in irrigation and water resource management must accompany and complement soil health management for blue water savings to be realized. A suite of agroecological and technical research approaches may resolve how building healthy soils impacts the effective use of water resources, specifically in irrigated systems, and help meet the global agricultural water challenge.

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Competing interests

The authors have declared that no competing interests exist.

Author contributions

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References

Abatzoglou, JT. 2013. Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology* **33**: 121–131. DOI: http://doi.org/10.1002/joc.3413.

Abatzoglou, JT. 2021. Climatology Lab. Available at https://www.climatologylab.org/gridmet.html. Accessed 01 February 2022.

Abawi, GS, **Widmer, TL**. 2000. Impact of soil health management practices on soilborne pathogens, nematodes and root diseases of vegetable crops. *Applied Soil Ecology* **15**: 37–47. DOI: https://doi.org/10.1016/S0929-1393(00)00070-6.

Acevedo, S, **Contreras, C**, **Martinez, S**, **Bonilla, C.** 2020. Estimating the unimodal and bimodal van Genuchten model parameters using the simplified evaporation and dewpoint methods. DOI: http://doi.org/10.5194/egusphere-egu2020-15082.

Acevedo-Opazo, C, **Ortega-Farias, S**, **Fuentes, S.** 2010. Effects of grapevine (*Vitis vinifera* L.) water status on water consumption, vegetative growth and grape quality: An irrigation scheduling application to achieve regulated deficit irrigation. *Agricultural Water Management* **97**: 956–964. DOI: http://doi.org/10.1016/j.agwat.2010.01.025.

Adesemoye, AO, **Egamberdieva, D.** 2013. Beneficial effects of plant growth-promoting rhizobacteria on improved crop production: Prospects for developing economies, in Maheshwari, DK, Saraf, M, Aeron, A eds., *Bacteria in agrobiology: Crop productivity*. Berlin, Germany: Springer: 45–63. DOI: http://doi.org/10.1007/978-3-642-37241-4_2.

Aggarwal, P, **Bhattacharyya, R**, **Mishra, AK**, **Das, TK**, **Šimůnek, J**, **Pramanik, P**, **Sudhishri, S**, **Vashisth, A**, **Krishnan, P**, **Chakraborty, D**, **Kamble, KH.** 2017. Modelling soil water balance and root water uptake in cotton grown under different soil conservation practices in the Indo-Gangetic Plain. *Agriculture, Ecosystems & Environment* **240**: 287–299. DOI: http://doi.org/10.1016/j.agee.2017.02.028.

Alcott, B. 2005. Jevons' paradox. *Ecological Economics* **54**: 9–21. DOI: http://doi.org/10.1016/j.ecolecon.2005.03.020.

Alegre, JC, **Cassel, DK**, **Amezquita, E.** 1991. Tillage systems and soil properties in Latin America. *Soil and Tillage Research* **20**: 147–163. DOI: http://doi.org/10.1016/0167-1987(91)90037-X.

Alhameid, A, **Singh, J**, **Sekaran, U**, **Ozlu, E**, **Kumar, S**, **Singh, S.** 2020. Crop rotational diversity impacts soil physical and hydrological properties under long-term no- and conventional-till soils. *Soil Research* **58**: 84. DOI: http://doi.org/10.1071/SR18192.

Alonso-Ayuso, M, **Quemada, M**, **Vanclooster, M**, **Ruiz-Ramos, M**, **Rodriguez, A**, **Gabriel, JL.** 2018. Assessing cover crop management under actual and climate change conditions. *Science of The Total Environment* **621**: 1330–1341. DOI: http://doi.org/10.1016/j.scitotenv.2017.10.095.

Alvarez, R, **Steinbach, HS**, **De Paepe, JL.** 2017. Cover crop effects on soils and subsequent crops in the pampas: A meta-analysis. *Soil and Tillage Research* **170**: 53–65. DOI: http://doi.org/10.1016/j.still.2017.03.005.

Arnold, JG, **Srinivasan, R**, **Muttiah, RS**, **Williams, JR.** 1998. Large area hydrologic modeling and assessment part I: Model development. *Journal of the American Water Resources Association* **34**: 73–89. DOI: http://doi.org/10.1111/j.1752-1688.1998.tb05961.x.

Assouline, S, **Russo, D**, **Silber, A**, **Or, D.** 2015. Balancing water scarcity and quality for sustainable irrigated agriculture: Balancing water scarcity and quality for irrigation. *Water Resources Research* **51**: 3419–3436. DOI: http://doi.org/10.1002/2015WR017071.

Augé, RM. 2001. Water relations, drought and vesicular-arbuscular mycorrhizal symbiosis. *Mycorrhiza* **11**: 3–42. DOI: https://doi.org/10.1007/s005720100097.

Augé, RM, **Toler, HD**, **Saxton, AM.** 2015. Arbuscular mycorrhizal symbiosis alters stomatal conductance of host plants more under drought than under amply watered conditions: A meta-analysis. *Mycorrhiza* **25**: 13–24. DOI: http://doi.org/10.1007/s00572-014-0585-4.

Austin, EE, **Wickings, K**, **McDaniel, MD**, **Robertson, GP**, **Grandy, AS.** 2017. Cover crop root contributions to soil carbon in a no-till corn bioenergy cropping system. *GCB Bioenergy* **9**: 1252–1263.

Bagnall, DK, **Morgan, CLS**, **Cope, M**, **Bean, GM**, **Cappellazzi, S**, **Greub, K**, **Liptzin, D**, **Norris, CL**, **Rieke, E**, **Tracy, P**, **Aberle, E**, **Ashworth, A**, **Bañuelos Tavarez, O**, **Bary, A**, **Baumhardt, RL**, **Borbón Gracia, A**, **Brainard, D**, **Brennan, J**, **Briones Reyes, D**, **Bruhjell, D**, **Carlyle, C**, **Crawford, J**, **Creech, C**, **Culman, S**, **Deen, W**, **Dell, C**, **Derner, J**, **Ducey, T**, **Duiker, SW**, **Dyck, M**, **Ellert, B**, **Entz,**

M, **Espinosa Solorio, A**, **Fonte, SJ**, **Fonteyne, S**, **Fortuna, A**, **Foster, J**, **Fultz, L**, **Gamble, AV**, **Geddes, C**, **Griffin-LaHue, D**, **Grove, J**, **Hamilton, SK**, **Hao, X**, **Hayden, ZD**, **Howe, J**, **Ippolito, J**, **Johnson, G**, **Kautz, M**, **Kitchen, N**, **Kumar, S**, **Kurtz, K**, **Larney, F**, **Lewis, K**, **Liebman, M**, **Lopez Ramirez, A**, **Machado, S**, **Maharjan, B**, **Martinez Gamiño, MA**, **May, W**, **McClaran, M**, **McDaniel, M**, **Millar, N**, **Mitchell, JP**, **Moore, PA**, **Moore, A**, **Mora Gutiérrez, M**, **Nelson, KA**, **Omondi, E**, **Osborne, S**, **Alcalá, LO**, **Owens, P**, **Pena-Yewtukhiw, EM**, **Poffenbarger, H**, **Ponce Lira, B**, **Reeve, J**, **Reinbott, T**, **Reiter, M**, **Ritchey, E**, **Roozeboom, KL**, **Rui, I**, **Sadeghpour, A**, **Sainju, UM**, **Sanford, G**, **Schillinger, W**, **Schindelbeck, RR**, **Schipanski, M**, **Schlegel, A**, **Scow, K**, **Sherrod, L**, **Sidhu, S**, **Solís Moya, E**, **St. Luce, M**, **Strock, J**, **Suyker, A**, **Sykes, V**, **Tao, H**, **Trujillo Campos, A**, **Van Eerd, LL**, **Verhulst, N**, **Vyn, TJ**, **Wang, Y**, **Watts, D**, **Wright, D**, **Zhang, T**, **Honeycutt, CW.** 2022. Carbon-sensitive pedotransfer functions for plant available water. *Soil Science Society of America Journal* **86**: 612–629. DOI: http://doi.org/10.1002/saj2.20395.

Balazs, C, **Morello-Frosch, R**, **Hubbard, A**, **Ray, I.** 2011. Social disparities in nitrate-contaminated drinking water in California's San Joaquin Valley. *Environmental Health Perspectives* **119**: 1272–1278. DOI: http://doi.org/10.1289/ehp.1002878.

Bano, Q, **Ilyas, N**, **Bano, A**, **Zafar, N**, **Akram, A**, **Hassan, F.** 2013. Effect of Azospirillum inoculation on maize (Zea mays L.) under drought stress. *Pakistan Journal of Botany* **45**: 13–20.

Bao, W. 2020. Crop-water management to reduce blue water scarcity: A case study for the Yellow River basin [Essay Master Thesis]. Available at https://purl.utwente.nl/essays/85460. Accessed 01 February 2022.

Barrios-Masias, FH, **Jackson, LE**. 2016. Increasing the effective use of water in processing tomatoes through alternate furrow irrigation without a yield decrease. *Agricultural Water Management* **177**: 107–117. DOI: https://doi.org/10.1016/j.agwat.2016.07.006.

Barrios-Masias, FH, **Lazcano, C**, **Hernandez-Espinosa, L.** 2019. Advances in understanding vegetable physiology: Root systems as the next frontier to improve sustainable vegetable production, in Hochmuth, G ed., *Achieving sustainable cultivation of vegetables*. Cambridge, UK: Burleigh Dodds Science Publishing.

Basche, AD, **DeLonge, MS.** 2017. The impact of continuous living cover on soil hydrologic properties: A meta-analysis. *Soil Science Society of America Journal* **81**: 1179–1190. DOI: http://doi.org/10.2136/sssaj2017.03.0077.

Basche, AD, **DeLonge, MS.** 2019. Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis. *PLoS One* **14**: e0215702. DOI: http://doi.org/10.1371/journal.pone.0215702.

Bastani, M, **Harter, T.** 2019. Source area management practices as remediation tool to address groundwater nitrate pollution in drinking supply wells. *Journal of Contaminant Hydrology* **226**: 103521. DOI: http://doi.org/10.1016/j.jconhyd.2019.103521.

Bekele, E, **Tilahun, S**, **Beyene, A**, **Asres, S**, **Geremew, B**, **Atinkut, H**. 2020. Soil water dynamics on irrigated garlic and pepper crops using Hydrus–1D model in the Lake Tana-Basin, Northwestern Ethiopia, in Habtu, NG, Ayele, DW, Fanta, SW, Admasu, BT, Bitew, MA eds., *Advances of Science and Technology, Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering*. Cham, Switzerland: Springer International Publishing: 193–209. DOI: https://doi.org/10.1007/978-3-030-43690-2_13.

Belimov, AA, **Dodd, IC**, **Hontzeas, N**, **Theobald, JC**, **Safronova, VI**, **Davies, WJ.** 2009. Rhizosphere bacteria containing 1-aminocyclopropane-1-carboxylate deaminase increase yield of plants grown in drying soil via both local and systemic hormone signalling. *New Phytologist* **181**: 413–423. DOI: http://doi.org/10.1111/j.1469-8137.2008.02657.x.

Bender, SF, **Wagg, C**, **van der Heijden, MGA.** 2016. An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. *Trends in Ecology & Evolution* **31**: 440–452. DOI: http://doi.org/10.1016/j.tree.2016.02.016.

Biemans, H, **Haddeland, I**, **Kabat, P**, **Ludwig, F**, **Hutjes, RWA**, **Heinke, J**, **von Bloh, W**, **Gerten, D.** 2011. Impact of reservoirs on river discharge and irrigation water supply during the 20th century: Impact of reservoirs on discharge and irrigation. *Water Resources Research* **47**. DOI: http://doi.org/10.1029/2009WR008929.

Bishopp, A, **Lynch, JP.** 2015. The hidden half of crop yields. *Nature Plants* **1**: 15117. DOI: http://doi.org/10.1038/nplants.2015.117.

Blum, A. 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field Crops Research* **112**: 119–123. DOI: http://doi.org/10.1016/j.fcr.2009.03.009.

Blundell, R, **Schmidt, JE**, **Igwe, A**, **Cheung, AL**, **Vannette, RL**, **Gaudin, ACM**, **Casteel, CL**. 2020. Organic management promotes natural pest control through altered plant resistance to insects. *Nature Plants* **6**: 483–491. DOI: https://doi.org/10.1038/s41477-020-0656-9.

Bolinder, MA, **Crotty, F**, **Elsen, A**, **Frac, M**, **Kismányoky, T**, **Lipiec, J**, **Tits, M**, **Tóth, Z**, **Kätterer, T.** 2020. The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: A synthesis of reviews. *Mitigation and Adaptation Strategies for Global Change* **25**: 929–952. DOI: http://doi.org/10.1007/s11027-020-09916-3.

Bonfante, A, **Basile, A**, **Bouma, J.** 2020. Targeting the soil quality and soil health concepts when aiming for the United Nations Sustainable Development

Goals and the EU Green Deal. *SOIL* **6**: 453–466. DOI: http://doi.org/10.5194/soil-6-453-2020.

Bowles, TM, **Barrios-Masias, FH**, **Carlisle, EA**, **Cavagnaro, TR**, **Jackson, LE**. 2016. Effects of arbuscular mycorrhizae on tomato yield, nutrient uptake, water relations, and soil carbon dynamics under deficit irrigation in field conditions. *Science of The Total Environment* **566–567**: 1223–1234. DOI: https://doi.org/10.1016/j.scitotenv.2016.05.178.

Bowles, TM, **Jackson, LE**, **Loeher, M**, **Cavagnaro, TR.** 2017. Ecological intensification and arbuscular mycorrhizas: A meta-analysis of tillage and cover crop effects. *Journal of Applied Ecology* **54**: 1785–1793. DOI: http://doi.org/10.1111/1365-2664.12815.

Bresson, J, **Vasseur, F**, **Dauzat, M**, **Labadie, M**, **Varoquaux, F**, **Touraine, B**, **Vile, D.** 2014. Interact to survive: *Phyllobacterium brassicacearum* improves arabidopsis tolerance to severe water deficit and growth recovery. *PLoS One* **9**: e107607. DOI: http://doi.org/10.1371/journal.pone.0107607.

Bünemann, EK, **Bongiorno, G**, **Bai, Z**, **Creamer, RE**, **De Deyn, G**, **de Goede, R**, **Fleskens, L**, **Geissen, V**, **Kuyper, TW**, **Mäder, P**, **Pulleman, M**, **Sukkel, W**, **van Groenigen, JW**, **Brussaard, L.** 2018. Soil quality—A critical review. *Soil Biology and Biochemistry* **120**: 105–125. DOI: http://doi.org/10.1016/j.soilbio.2018.01.030.

Burke, JA, **Lewis, KL**, **Ritchie, GL**, **DeLaune, PB**, **Keeling, JW**, **Acosta-Martinez, V**, **Moore, JM**, **McLendon, T.** 2021. Net positive soil water content following cover crops with no tillage in irrigated semi-arid cotton production. *Soil and Tillage Research* **208**: 104869. DOI: http://doi.org/10.1016/j.still.2020.104869.

California Department of Food and Agriculture. 2022. Healthy Soils Program. Available at https://www.cdfa.ca.gov/oefi/healthysoils/. Accessed 01 February 2022.

Cano, A, **Núñez, A**, **Acosta-Martinez, V**, **Schipanski, M**, **Ghimire, R**, **Rice, C**, **West, C.** 2018. Current knowledge and future research directions to link soil health and water conservation in the Ogallala Aquifer region. *Geoderma* **328**: 109–118. DOI: http://doi.org/10.1016/j.geoderma.2018.04.027.

Carlisle, L. 2016. Factors influencing farmer adoption of soil health practices in the United States: A narrative review. *Agroecology and Sustainable Food Systems* **40**: 583–613. DOI: http://doi.org/10.1080/21683565.2016.1156596.

Carlisle, L, **Esquivel, K**, **Baur, P**, **Ichikawa, NF**, **Olimpi, EM**, **Ory, J**, **Waterhouse, H**, **Iles, A**, **Karp, DS**, **Kremen, C**, **Bowles, TM.** 2022. Organic farmers face persistent barriers to adopting diversification practices in California's Central Coast. *Agroecology and Sustainable Food Systems* **46**: 1145–1172. DOI: http://doi.org/10.1080/21683565.2022.2104420.

Carlson, S, **Stockwell, R.** 2013. Research priorities for advancing adoption of cover crops in agriculture-intensive regions. *Journal of Agriculture, Food Systems, and Community Development* **3**: 125–129.

Chagnon, P-L, **Bradley, RL**, **Maherali, H**, **Klironomos, JN.** 2013. A trait-based framework to understand life history of mycorrhizal fungi. *Trends in Plant Science* **18**: 484–491. DOI: http://doi.org/10.1016/j.tplants.2013.05.001.

Chandrasekhar, P, **Kreiselmeier, J**, **Schwen, A**, **Weninger, T**, **Julich, S**, **Feger, K-H**, **Schwärzel, K.** 2019. SPorDyn: A Python code for modeling the evolution of soil pore size distribution after tillage. *MethodsX* **6**: 2118–2126. DOI: http://doi.org/10.1016/j.mex.2019.09.014.

Chang, W, **Sui, X**, **Fan, X-X**, **Jia, T-T**, **Song, F-Q.** 2018. Arbuscular mycorrhizal symbiosis modulates antioxidant response and ion distribution in salt-stressed *Elaeagnus angustifolia* seedlings. *Frontiers in Microbiology* **9**: 652. DOI: http://doi.org/10.3389/fmicb.2018.00652.

Chartzoulakis, K, **Bertaki, M.** 2015. Sustainable water management in agriculture under climate change. *Agriculture and Agricultural Science Procedia* **4**: 88–98. DOI: http://doi.org/10.1016/j.aaspro.2015.03.011.

Chauhan, H, **Bagyaraj, DJ**, **Selvakumar, G**, **Sundaram, SP.** 2015. Novel plant growth promoting rhizobacteria—Prospects and potential. *Applied Soil Ecology* **95**: 38–53. DOI: http://doi.org/10.1016/j.apsoil.2015.05.011.

Chen, Y, **Zhou, Y**, **Fang, S**, **Li, M**, **Wang, Y**, **Cao, K.** 2022. Crop pattern optimization for the coordination between economy and environment considering hydrological uncertainty. *Science of The Total Environment* **809**: 151152. DOI: http://doi.org/10.1016/j.scitotenv.2021.151152.

Chiarelli, DD, **Passera, C**, **Rosa, L**, **Davis, KF**, **D'Odorico, P**, **Rulli, MC.** 2020. The green and blue crop water requirement WATNEEDS model and its global gridded outputs. *Scientific Data* **7**: 273. DOI: http://doi.org/10.1038/s41597-020-00612-0.

Chukalla, AD, **Krol, MS**, **Hoekstra, AY.** 2015. Green and blue water footprint reduction in irrigated agriculture: Effect of irrigation techniques, irrigation strategies and mulching. *Hydrology and Earth System Sciences* **19**: 4877–4891. DOI: http://doi.org/10.5194/hess-19-4877-2015.

Cohen, AC, **Travaglia, CN**, **Bottini, R**, **Piccoli, PN.** 2009. Participation of abscisic acid and gibberellins produced by endophytic *Azospirillum* in the alleviation of drought effects in maize. *Botany* **87**: 455–462. DOI: http://doi.org/10.1139/B09-023.

Cooley, H. 2020. *Urban and agricultural water use in California, 1960–2015*. Oakland, CA: Pacific Institute. Available at https://pacinst.org/wpcontent/uploads/2020/06/PI_Water_Use_Trends_June_2020.pdf. Accessed 01 February 2022.

Cousins, OH, **Garnett, TP**, **Rasmussen, A**, **Mooney, SJ**, **Smernik, RJ**, **Brien, CJ**, **Cavagnaro, TR.** 2020. Variable water cycles have a greater impact on wheat growth and soil nitrogen response than constant watering. *Plant Science* **290**: 110146. DOI: http://doi.org/10.1016/j.plantsci.2019.05.009.

Cueff, S, **Coquet, Y**, **Aubertot, J-N**, **Bel, L**, **Pot, V**, **Alletto, L**. 2021. Estimation of soil water retention in conservation agriculture using published and new pedotransfer functions. *Soil and Tillage Research* **209**: 104967. DOI: https://doi.org/10.1016/j.still.2021.104967.

Dahlke, HE, **Brown, AG**, **Orloff, S**, **Putnam, D**, **O'Geen, T.** 2018. Managed winter flooding of alfalfa recharges groundwater with minimal crop damage. *California Agriculture Journal* **72**: 1–11. DOI: http://doi.org/10.3733/ca.2018a0001.

Dang, TD, **Chowdhury, AFMK**, **Galelli, S.** 2020. On the representation of water reservoir storage and operations in large-scale hydrological models: Implications on model parameterization and climate change impact assessments. *Hydrology and Earth System Sciences* **24**: 397–416. DOI: http://doi.org/10.5194/hess-24-397-2020.

Darnhofer, I. 2014. Resilience and why it matters for farm management. *European Review of Agricultural Economics* **41**: 461–484. DOI: http://doi.org/10.1093/erae/jbu012.

Daryanto, S, **Fu, B**, **Wang, L**, **Jacinthe, P-A**, **Zhao, W.** 2018. Quantitative synthesis on the ecosystem services of cover crops. *Earth-Science Reviews* **185**: 357–373. DOI: http://doi.org/10.1016/j.earscirev.2018.06.013.

de Groot, RS, **Alkemade, R**, **Braat, L**, **Hein, L**, **Willemen, L.** 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity* **7**: 260–272. DOI: http://doi.org/10.1016/j.ecocom.2009.10.006.

de Jonge, LW, **Moldrup, P**, **Schjønning, P.** 2009. Soil infrastructure, interfaces & translocation processes in inner space ("Soil-it-is"): Towards a road map for the constraints and crossroads of soil architecture and biophysical processes. *Hydrology and Earth System Sciences* **13**: 1485–1502. DOI: http://doi.org/10.5194/hess-13-1485-2009.

DeVincentis, A, **Solis, SS**, **Rice, S**, **Zaccaria, D**, **Snyder, R**, **Maskey, M**, **Gomes, A**, **Gaudin, A**, **Mitchell, J.** 2022. Impacts of winter cover cropping on soil moisture and evapotranspiration in California's specialty crop fields may be minimal during winter months. *California Agriculture Journal* **76**: 1–9. DOI: http://doi.org/10.3733/ca.2022a0001.

Devine, S, **O'Geen, A.** 2019. Climate-smart management of soil water storage: Statewide analysis of California perennial crops. *Environmental Research Letters* **14**: 044021. DOI: http://doi.org/10.1088/1748-9326/ab058c.

Dias, T, **Dukes, A**, **Antunes, PM.** 2015. Accounting for soil biotic effects on soil health and crop productivity in the design of crop rotations. *Journal of the Science of Food and Agriculture* **95**: 447–454. DOI: http://doi.org/10.1002/jsfa.6565.

Dodd, IC, **Zinovkina, NY**, **Safronova, VI**, **Belimov, AA.** 2010. Rhizobacterial mediation of plant hormone status. *Annals of Applied Biology* **157**: 361–379. DOI: http://doi.org/10.1111/j.1744-7348.2010.00439.x.

Dong, L, **Zhang, W**, **Xiong, Y**, **Zou, J**, **Huang, Q**, **Xu, X**, **Ren, P**, **Huang, G.** 2022. Impact of short-term organic amendments incorporation on soil structure and hydrology in semiarid agricultural lands. *International Soil and Water Conservation Research* **10**: 457–469. DOI: http://doi.org/10.1016/j.iswcr.2021.10.003.

Downer, J, **Hodel, D.** 2001. The effects of mulching on establishment of *Syagrus romanzoffiana* (Cham.) *Becc., Washingtonia robusta* H. Wendl. *and Archontophoenix cunninghamiana* (H. Wendl.) H. Wendl. & Drude in the landscape. *Scientia Horticulturae* **87**: 85–92. DOI: http://doi.org/10.1016/S0304-4238(00)00171-0.

Duan, X, **Neuman, DS**, **Reiber, JM**, **Green, CD**, **Saxton, AM**, **Augé, RM.** 1996. Mycorrhizal influence on hydraulic and hormonal factors implicated in the control of stomatal conductance during drought. *Journal of Experimental Botany* **47**: 1541–1550. DOI: http://doi.org/10.1093/jxb/47.10.1541.

Duc, NH, **Csintalan, Z**, **Posta, K.** 2018. Arbuscular mycorrhizal fungi mitigate negative effects of combined drought and heat stress on tomato plants. *Plant Physiology and Biochemistry* **132**: 297–307. DOI: http://doi.org/10.1016/j.plaphy.2018.09.011.

Dumont, A, **Mayor, B**, **López-Gunn, E.** 2013. Is the rebound effect or Jevons paradox a useful concept for better management of water resources? Insights from the irrigation modernisation process in Spain. *Aquatic Procedia* **1**: 64–76. DOI: http://doi.org/10.1016/j.aqpro.2013.07.006.

Ernst, G, **Emmerling, C**. 2009. Impact of five different tillage systems on soil organic carbon content and the density, biomass, and community composition of earthworms after a ten year period. *European Journal of Soil Biology* **45**: 247–251. DOI: https://doi.org/10.1016/j.ejsobi.2009.02.002.

Escriva-Bou, A, **Hui, R**, **Maples, S**, **Medellín-Azuara, J**, **Harter, T**, **Lund, JR.** 2020. Planning for groundwater sustainability accounting for uncertainty and costs: An application to California's Central Valley. *Journal of Environmental Management* **264**: 110426. DOI: http://doi.org/10.1016/j.jenvman.2020.110426.

Evenson, G, **Osterholz, WR**, **Shedekar, VS**, **King, K**, **Mehan, S**, **Kalcic, M.** 2022. Representing soil health practice effects on soil properties and nutrient loss in a watershed-scale hydrologic model. *Journal of Environmental Quality.* DOI: http://doi.org/10.1002/jeq2.20338.

Falkenmark, M, **Rockström, J.** 2010. Building water resilience in the face of global change: From a blue-only to a green-blue water approach to land-water management. *Journal of Water Resources Planning and*

Management **136**: 606–610. DOI: http://doi.org/10.1061/(ASCE)WR.1943-5452.0000118.

Faunt, CC, **Sneed, M**, **Traum, J**, **Brandt, JT.** 2016. Water availability and land subsidence in the Central Valley, California, USA. *Hydrogeology Journal* **24**: 675–684. DOI: http://doi.org/10.1007/s10040-015-1339-x.

Figueiredo, MVB, **Martinez, CR**, **Burity, HA**, **Chanway, CP.** 2008. Plant growth-promoting rhizobacteria for improving nodulation and nitrogen fixation in the common bean (*Phaseolus vulgaris* L.). *World Journal of Microbiology and Biotechnology* **24**: 1187–1193. DOI: http://doi.org/10.1007/s11274-007-9591-4.

Fischer, C, **Tischer, J**, **Roscher, C**, **Eisenhauer, N**, **Ravenek, J**, **Gleixner, G**, **Attinger, S**, **Jensen, B**, **de Kroon, H**, **Mommer, L**, **Scheu, S**, **Hildebrandt, A.** 2015. Plant species diversity affects infiltration capacity in an experimental grassland through changes in soil properties. *Plant Soil* **397**: 1–16. DOI: http://doi.org/10.1007/s11104-014-2373-5.

Flint, LE, **Flint, AL**, **Mendoza, J**, **Kalansky, J**, **Ralph, FM.** 2018. Characterizing drought in California: New drought indices and scenario-testing in support of resource management. *Ecological Processes* **7**: 1. DOI: http://doi.org/10.1186/s13717-017-0112-6.

Flint, LE, **Flint, AL**, **Thorne, JH**, **Boynton, R.** 2013. Fine-scale hydrologic modeling for regional landscape applications: The California Basin Characterization Model development and performance. *Ecological Processes* **2**: 25. DOI: http://doi.org/10.1186/2192-1709-2-25.

Folke, C, **Carpenter, SR**, **Walker, B**, **Scheffer, M**, **Chapin, T**, **Rockström, J.** 2010. Resilience thinking: Integrating resilience, adaptability and transformability. *Ecology and Society* **15**(4): art20. DOI: http://doi.org/10.5751/ES-03610-150420.

Fonte, SJ, **Barrios, E**, **Six, J.** 2010. Earthworms, soil fertility and aggregate-associated soil organic matter dynamics in the Quesungual agroforestry system. *Geoderma* **155**: 320–328. DOI: http://doi.org/10.1016/j.geoderma.2009.12.016.

Franzluebbers, A. 2007. USDA–Agricultural Research Service. Soil physical aspects of integrated crop-livestock systems. Available at https://www.ars.usda.gov/ARSUserFiles/66120900/SoilManagementAndCarbonSequestration/2007ajfP02%20-%20Soil%20physical%20aspects%20of%20ICL%20-%20ICLS%20Brazil.pdf. Accessed 01 February 2022.

Gabriel, JL, **Muñoz-Carpena, R**, **Quemada, M.** 2012. The role of cover crops in irrigated systems: Water balance, nitrate leaching and soil mineral nitrogen accumulation. *Agriculture, Ecosystems & Environment* **155**: 50–61. DOI: http://doi.org/10.1016/j.agee.2012.03.021.

Galdos, MV, **Pires, LF**, **Cooper, HV**, **Calonego, JC**, **Rosolem, CA**, **Mooney, SJ.** 2019. Assessing the long-term effects of zero-tillage on the macroporosity of Brazilian soils using X-ray computed tomography. *Geoderma* **337**: 1126–1135. DOI: http://doi.org/10.1016/j.geoderma.2018.11.031.

García-Tejera, O, **López-Bernal, Á**, **Orgaz, F**, **Testi, L**, **Villalobos, FJ.** 2018. Are olive root systems optimal for deficit irrigation? *European Journal of Agronomy* **99**: 72–79. DOI: http://doi.org/10.1016/j.eja.2018.06.012.

Garret, A. 2019. Dry farming in the Maritime Pacific Northwest: Intro to dry farming organic vegetables. Available at https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/em9229.pdf. Accessed 01 February 2022.

Gaudin, ACM, **Tolhurst, TN**, **Ker, AP**, **Janovicek, K**, **Tortora, C**, **Martin, RC**, **Deen, W.** 2015. Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS One* **10**: e0113261. DOI: http://doi.org/10.1371/journal.pone.0113261.

Gilbert, ME, **Medina, V.** 2016. Drought adaptation mechanisms should guide experimental design. *Trends in Plant Science* **21**: 639–647. DOI: http://doi.org/10.1016/j.tplants.2016.03.003.

Glick, BR, **Cheng, Z**, **Czarny, J**, **Duan, J.** 2007. Promotion of plant growth by ACC deaminase-producing soil bacteria. *European Journal of Plant Pathology* **119**: 329–339. DOI: http://doi.org/10.1007/s10658-007-9162-4.

Glick, BR, **Penrose, DM**, **Li, J.** 1998. A model for the lowering of plant ethylene concentrations by plant growth-promoting bacteria. *Journal of Theoretical Biology* **190**: 63–68. DOI: http://doi.org/10.1006/jtbi.1997.0532.

Gómez, JA, **Ben-Gal, A**, **Alarcón, JJ**, **De Lannoy, G**, **de Roos, S**, **Dostál, T**, **Fereres, E**, **Intrigliolo, DS**, **Krása, J**, **Klik, A**, **Liebhard, G**, **Nolz, R**, **Peeters, A**, **Plaas, E**, **Quinton, JN**, **Miao, R**, **Strauss, P**, **Xu, W**, **Zhang, Z**, **Zhong, F**, **Zumr, D**, **Dodd, IC.** 2020. SHui, an EU-Chinese cooperative project to optimize soil and water management in agricultural areas in the XXI century. *International Soil and Water Conservation Research* **8**: 1–14. DOI: http://doi.org/10.1016/j.iswcr.2020.01.001.

Grover, M, **Madhubala, R**, **Ali, SkZ**, **Yadav, SK**, **Venkateswarlu, B.** 2014. Influence of *Bacillus* spp. strains on seedling growth and physiological parameters of sorghum under moisture stress conditions: *Bacillus* spp. strains influence sorghum under moisture stress. *Journal of Basic Microbiology* **54**: 951–961. DOI: http://doi.org/10.1002/jobm.201300250.

Gupta, R, **Tyagi, NK**, **Abrol, I.** 2020. Rainwater management and Indian agriculture: A call for a shift in focus from blue to green water. *Journal: Agricultural Research* **9**: 429–443. DOI: http://doi.org/10.1007/s40003-020-00467-2.

Guzman, A, **Montes, M**, **Hutchins, L**, **DeLaCerda, G**, **Yang, P**, **Kakouridis, A**, **Dahlquist-Willard, RM**, **Firestone, MK**, **Bowles, T**, **Kremen, C.** 2021. Crop diversity enriches arbuscular mycorrhizal fungal communities in an intensive agricultural landscape. *New Phytologist* **231**: 447–459. DOI: http://doi.org/10.1111/nph.17306.

Hamilton, AJ, **Stagnitti, F**, **Xiong, X**, **Kreidl, SL**, **Benke, KK**, **Maher, P.** 2007. Wastewater irrigation: The state of play. *Vadose Zone Journal* **6**: 823–840. DOI: http://doi.org/10.2136/vzj2007.0026.

Han, E, **Kautz, T**, **Perkons, U**, **Uteau, D**, **Peth, S**, **Huang, N**, **Horn, R**, **Köpke, U.** 2015. Root growth dynamics inside and outside of soil biopores as affected by crop sequence determined with the profile wall method. *Biology and Fertility of Soils* **51**: 847–856. DOI: http://doi.org/10.1007/s00374-015-1032-1.

Han, M, **Zhao, C**, **Šimůnek, J**, **Feng, G.** 2015. Evaluating the impact of groundwater on cotton growth and root zone water balance using Hydrus-1D coupled with a crop growth model. *Agricultural Water Management* **160**: 64–75. DOI: http://doi.org/10.1016/j.agwat.2015.06.028.

Hanson, B, **Orloff, S**, **Peters, D.** 2000. Monitoring soil moisture helps refine irrigation management. *California Agriculture* **54**: 38–42.

Harter, T. 2015. California's agricultural regions gear up to actively manage groundwater use and protection. *California Agriculture* **69**: 193–201.

Hatfield, JL, **Boote, KJ**, **Kimball, BA**, **Ziska, LH**, **Izaurralde, RC**, **Ort, D**, **Thomson, AM**, **Wolfe, D.** 2011. Climate impacts on agriculture: Implications for crop production. *Agronomy Journal* **103**: 351–370. DOI: http://doi.org/10.2134/agronj2010.0303.

Hoekstra, AY. 2019. Green-blue water accounting in a soil water balance. *Advances in Water Resources* **129**: 112–117. DOI: http://doi.org/10.1016/j.advwatres.2019.05.012.

Howitt, R, **MacEwan, D**, **Medellín-Azuara, J**, **Lund, J**, **Sumner, D.** 2015. *Economic analysis of the 2015 drought for California agriculture*. Davis, CA: UC-Davis Center for Watershed Sciences.

Huang, N, **Athmann, M**, **Han, E.** 2020. Biopore-induced deep root traits of two winter crops. *Agriculture* **10**: 634. DOI: http://doi.org/10.3390/agriculture10120634.

Huang, Z, **Hejazi, M**, **Tang, Q**, **Vernon, CR**, **Liu, Y**, **Chen, M**, **Calvin, K.** 2019. Global agricultural green and blue water consumption under future climate and land use changes. *Journal of Hydrology* **574**: 242–256. DOI: http://doi.org/10.1016/j.jhydrol.2019.04.046.

Hudson, BD. 1984. Soil organic matter and available water capacity. *Journal of Soil and Water Conservation* **49**: 189.

Hunink, J, **Vila, M**, **Baille, A**. 2011. REDSIM: Approach to soil water modelling. Tools and data considerations to provide relevant soil water information for deficit irrigation [Unpublished report]. Wageningen, the Netherlands: FutureWater.

Iqbal, R, **Raza, MAS**, **Saleem, MF**, **Khan, IH**, **Ahmad, S**, **Zaheer, MS**, **Aslam, MU**, **Haider, I.** 2019. Physiological and biochemical appraisal for mulching and partial rhizosphere drying of cotton. *Journal of Arid Land* **11**: 785–794. DOI: http://doi.org/10.1007/s40333-019-0014-9.

Iwanaga, T, **Partington, D**, **Ticehurst, J**, **Croke, BFW**, **Jakeman, AJ.** 2020. A socio-environmental model for exploring sustainable water management futures: Participatory and collaborative modelling in the Lower Campaspe catchment. *Journal of Hydrology: Regional Studies* **28**: 100669. DOI: http://doi.org/10.1016/j.ejrh.2020.100669.

Jackson, LE, **Koch, GW.** 1997. The ecophysiology of crops and their wild relatives, in Jackson, LE ed., *Ecology in agriculture*. Amsterdam, the Netherlands: Elsevier: 3–37. DOI: http://doi.org/10.1016/B978-012378260-1/50002-6.

Jägermeyr, J, **Gerten, D**, **Schaphoff, S**, **Heinke, J**, **Lucht, W**, **Rockström, J.** 2016. Integrated crop water management might sustainably halve the global food gap. *Environmental Research Letters* **11**: 025002. DOI: http://doi.org/10.1088/1748-9326/11/2/025002.

Jahanzad, E, **Holtz, BA**, **Zuber, CA**, **Doll, D**, **Brewer, KM**, **Hogan, S**, **Gaudin, ACM.** 2020. Orchard recycling improves climate change adaptation and mitigation potential of almond production systems. *PLoS One* **15**: e0229588. DOI: http://doi.org/10.1371/journal.pone.0229588.

Jasechko, S, **Perrone, D.** 2021. Global groundwater wells at risk of running dry. *Science* **372**: 418–421. DOI: http://doi.org/10.1126/science.abc2755.

Jensen, JL, **Schjønning, P**, **Watts, CW**, **Christensen, BT**, **Munkholm, LJ.** 2019. Soil water retention: Unimodal models of pore-size distribution neglect impacts of soil management. *Soil Science Society of America Journal* **83**: 18–26. DOI: http://doi.org/10.2136/sssaj2018.06.0238.

Jewitt, G. 2006. Integrating blue and green water flows for water resources management and planning. *Physics and Chemistry of the Earth, Parts A/B/C* **31**: 753–762. DOI: http://doi.org/10.1016/j.pce.2006.08.033.

Jimenez, B, **Asano, T.** 2008. Water reuse: An international survey of current practice, issues and needs. *Water Intelligence Online* **7**: 9781780401881. DOI: http://doi.org/10.2166/9781780401881.

Jokela, D, **Nair, A.** 2016. Effects of reduced tillage and fertilizer application method on plant growth, yield, and soil health in organic bell pepper production. *Soil and Tillage Research* **163**: 243–254. DOI: http://doi.org/10.1016/j.still.2016.06.010.

Jones, C, **Olson-Rutz, K**, **Miller, P**, **Zabinski, C.** 2020. Cover crop management in semi-arid regions: Effect on soil and cash crop. *Crops & Soils Magazine* **53**: 42–51. DOI: http://doi.org/10.1002/crso.20065.

Jouma, N, **Dadaser-Celik, , F**. 2021. Assessing hydrologic alterations due to reservoirs and intensified irrigation in a semi-arid agricultural river basin using SWAT*. *Irrigation and Drainage* **71**(2): 452–471. DOI: http://doi.org/10.1002/ird.2661.

Kallenbach, C, **Grandy, AS.** 2011. Controls over soil microbial biomass responses to carbon amendments in agricultural systems: A meta-analysis. *Agriculture,* *Ecosystems and Environment* **144**: 241–252. DOI: http://doi.org/10.1016/j.agee.2011.08.020.

Karandish, F, **Šimůnek, J.** 2019. A comparison of the HYDRUS (2D/3D) and SALTMED models to investigate the influence of various water-saving irrigation strategies on the maize water footprint. *Agricultural Water Management* **213**: 809–820. DOI: http://doi.org/10.1016/j.agwat.2018.11.023.

Keesstra, S, **Sannigrahi, S**, **López-Vicente, M**, **Pulido, M**, **Novara, A**, **Visser, S**, **Kalantari, Z.** 2021. The role of soils in regulation and provision of blue and green water. *Philosophical Transactions of the Royal Society B* **376**: 20200175. DOI: http://doi.org/10.1098/rstb.2020.0175.

Kemanian, AR, **Julich, S**, **Manoranjan, VS**, **Arnold, JR.** 2011. Integrating soil carbon cycling with that of nitrogen and phosphorus in the watershed model SWAT: Theory and model testing. *Ecological Modelling* **222**: 1913–1921. DOI: http://doi.org/10.1016/j.ecolmodel.2011.03.017.

Khan, T, **Nouri, H**, **Booij, M**, **Hoekstra, A**, **Khan, H**, **Ullah, I.** 2021. Water footprint, blue water scarcity, and economic water productivity of irrigated crops in Peshawar Basin, Pakistan. *Water* **13**: 1249. DOI: http://doi.org/10.3390/w13091249.

Kim, SG, **Khan, Z**, **Jeon, YH**, **Kim, YH.** 2009. Inhibitory effect of *Paenibacillus polymyxa* GBR-462 on *Phytophthora capsici* causing phytophthora blight in chili pepper. *Journal of Phytopathology* **157**: 329–337. DOI: http://doi.org/10.1111/j.1439-0434.2008.01490.x.

King, AE, **Ali, GA**, **Gillespie, AW**, **Wagner-Riddle, C.** 2020. Soil organic matter as catalyst of crop resource capture. *Frontiers in Environmental Science* **8**: 50. DOI: http://doi.org/10.3389/fenvs.2020.00050.

Kinoshita, R, **Schindelbeck, RR**, **van Es, HM.** 2017. Quantitative soil profile-scale assessment of the sustainability of long-term maize residue and tillage management. *Soil and Tillage Research* **174**: 34–44. DOI: http://doi.org/10.1016/j.still.2017.05.010.

Klocke, NL, **Currie, RS**, **Aiken, RM.** 2009. Soil water evaporation and crop residues. *Transactions of the ASABE* **52**: 103–110. DOI: http://doi.org/10.13031/2013.25951.

Kocis, TN, **Dahlke, HE.** 2017. Availability of high-magnitude streamflow for groundwater banking in the Central Valley, California. *Environmental Research Letters* **12**: 084009. DOI: http://doi.org/10.1088/1748-9326/aa7b1b.

Kodešová, R, **Vignozzi, N**, **Rohošková, M**, **Hájková, T**, **Kočárek, M**, **Pagliai, M**, **Kozák, J**, **Šimůnek, J.** 2009. Impact of varying soil structure on transport processes in different diagnostic horizons of three soil types. *Journal of Contaminant Hydrology* **104**: 107–125. DOI: http://doi.org/10.1016/j.jconhyd.2008.10.008.

Kong, AYY, **Six, J.** 2010. Tracing root vs. residue carbon into soils from conventional and alternative cropping systems. *Soil Science Society of America Journal* **74**: 1201–1210. DOI: http://doi.org/10.2136/sssaj2009.0346.

Kranz, CN, **McLaughlin, RA**, **Johnson, A**, **Miller, G**, **Heitman, JL**. 2020. The effects of compost incorporation on soil physical properties in urban soils—A concise review. *Journal of Environmental Management* **261**: 110209. DOI: https://doi.org/10.1016/j.jenvman.2020.110209.

Kroes, J, **Supit, I**, **Van Dam, J**, **Van Walsum, P**, **Mulder, M.** 2017. Impact of capillary rise and recirculation on crop yields (preprint). *Vadose Zone Hydrology/Modelling Approaches*. DOI: http://doi.org/10.5194/hess-2017-223.

Larkin, RP. 2015. Soil health paradigms and implications for disease management. *Annual Review of Phytopathology* **53**: 199–221. DOI: https://doi.org/10.1146/annurev-phyto-080614-120357.

Lazcano, C, **Barrios-Masias, FH**, **Jackson, LE.** 2014. Arbuscular mycorrhizal effects on plant water relations and soil greenhouse gas emissions under changing moisture regimes. *Soil Biology and Biochemistry* **74**: 184–192. DOI: http://doi.org/10.1016/j.soilbio.2014.03.010.

Leap, J, **Yogg-Comerchero, K**, **Wong, D.** 2017. Organic mixed production blocks for direct markets on California's Central Coast: A guide for beginning specialty crop growers. Available at https://agroecology.ucsc.edu/about/publications/grower-guides/pdf-downloads/csa-production-blocks.pdf. Accessed 01 February 2022.

Lei, C, **Wagner, PD**, **Fohrer, N.** 2021. Influences of land use changes on the dynamics of water quantity and quality in the German lowland catchment of the Stör (preprint). *Catchment Hydrology/Modelling Approaches*. DOI: http://doi.org/10.5194/hess-2021-476.

Lepsch, HC, **Brown, PH**, **Peterson, CA**, **Gaudin, ACM**, **Khalsa, SDS.** 2019. Impact of organic matter amendments on soil and tree water status in a California orchard. *Agricultural Water Management* **222**: 204–212. DOI: http://doi.org/10.1016/j.agwat.2019.06.002.

Li, J, **Meng, B**, **Chai, H**, **Yang, X**, **Song, W**, **Li, S**, **Lu, A**, **Zhang, T**, **Sun, W.** 2019. Arbuscular mycorrhizal fungi alleviate drought stress in C3 (*Leymus chinensis)* and C4 *(Hemarthria altissima*) grasses via altering antioxidant enzyme activities and photosynthesis. *Frontiers in Plant Science* **10**: 499. DOI: http://doi.org/10.3389/fpls.2019.00499.

Li, M, **Schmidt, JE**, **LaHue, DG**, **Lazicki, P**, **Kent, A**, **Machmuller, MB**, **Scow, KM**, **Gaudin, ACM.** 2020. Impact of irrigation strategies on tomato root distribution and rhizosphere processes in an organic system. *Frontiers in Plant Science* **11**: 360. DOI: http://doi.org/10.3389/fpls.2020.00360.

Li, Q, **Dong, B**, **Qiao, Y**, **Liu, M**, **Zhang, J.** 2010. Root growth, available soil water, and water-use efficiency of winter wheat under different irrigation regimes applied at different growth stages in North China.

Agricultural Water Management **97**: 1676–1682. DOI: http://doi.org/10.1016/j.agwat.2010.05.025.

Lipan, L, **Martín-Palomo, MJ**, **Sánchez-Rodríguez, L**, **Cano-Lamadrid, M**, **Sendra, E**, **Hernández, F**, **Burló, F**, **Vázquez-Araújo, L**, **Andreu, L**, **Carbonell-Barrachina, ÁA.** 2019. Almond fruit quality can be improved by means of deficit irrigation strategies. *Agricultural Water Management* **217**: 236–242. DOI: http://doi.org/10.1016/j.agwat.2019.02.041.

López-Moreno, JI, **Gascoin, S**, **Herrero, J**, **Sproles, EA**, **Pons, M**, **Alonso-González, E**, **Hanich, L**, **Boudhar, A**, **Musselman, KN**, **Molotch, NP**, **Sickman, J**, **Pomeroy, J.** 2017. Different sensitivities of snowpacks to warming in Mediterranean climate mountain areas. *Environmental Research Letters* **12**: 074006. DOI: http://doi.org/10.1088/1748-9326/aa70cb.

Lotter, DW, **Seidel, R**, **Liebhardt, W.** 2003. The performance of organic and conventional cropping systems in an extreme climate year. *American Journal of Alternative Agriculture* **18**: 146–154. DOI: http://doi.org/10.1079/AJAA200345.

Luan, X-B, **Yin, Y-L**, **Wu, P-T**, **Sun, S-K**, **Wang, Y-B**, **Gao, X-R**, **Liu, J.** 2018. An improved method for calculating the regional crop water footprint based on a hydrological process analysis. *Hydrology and Earth System Sciences* **22**: 5111–5123. DOI: http://doi.org/10.5194/hess-22-5111-2018.

Lubell, M, **Blomquist, W**, **Beutler, L.** 2020. Sustainable groundwater management in California: A grand experiment in environmental governance. *Society & Natural Resources* **33**: 1447–1467. DOI: http://doi.org/10.1080/08941920.2020.1833617.

Lutz, F, **Herzfeld, T**, **Heinke, J**, **Rolinski, S**, **Schaphoff, S**, **von Bloh, W**, **Stoorvogel, JJ**, **Müller, C.** 2019. Simulating the effect of tillage practices with the global ecosystem model LPJmL (Version 5.0-tillage). *Geoscientific Model Development* **12**: 2419–2440. DOI: http://doi.org/10.5194/gmd-12-2419-2019.

Maharjan, GR, **Prescher, A-K**, **Nendel, C**, **Ewert, F**, **Mboh, CM**, **Gaiser, T**, **Seidel, SJ.** 2018. Approaches to model the impact of tillage implements on soil physical and nutrient properties in different agroecosystem models. *Soil and Tillage Research* **180**: 210–221. DOI: http://doi.org/10.1016/j.still.2018.03.009.

Mallmann, FJK, **Rheinheimer, DDS**, **Ceretta, CA**, **Cella, C**, **Minella, JPG**, **Guma, RL**, **Filipović, V**, **van Oort, F**, **Šimůnek, J.** 2014. Soil tillage to reduce surface metal contamination—Model development and simulations of zinc and copper concentration profiles in a pig slurry-amended soil. *Agriculture, Ecosystems & Environment* **196**: 59–68. DOI: http://doi.org/10.1016/j.agee.2014.06.024.

Mardhiah, U, **Caruso, T**, **Gurnell, A**, **Rillig, MC.** 2016. Arbuscular mycorrhizal fungal hyphae reduce soil erosion by surface water flow in a greenhouse experiment. *Applied Soil Ecology* **99**: 137–140. DOI: http://doi.org/10.1016/j.apsoil.2015.11.027.

Mariotte, P, **Mehrabi, Z**, **Bezemer, TM**, **De Deyn, GB**, **Kulmatiski, A**, **Drigo, B**, **Veen, GF**, **van der Heijden, MGA**, **Kardol, P.** 2018. Plant–soil feedback: Bridging natural and agricultural sciences. *Trends in Ecology & Evolution* **33**: 129–142. DOI: http://doi.org/10.1016/j.tree.2017.11.005.

Martínez, E, **Fuentes, J-P**, **Silva, P**, **Valle, S**, **Acevedo, E.** 2008. Soil physical properties and wheat root growth as affected by no-tillage and conventional tillage systems in a Mediterranean environment of Chile. *Soil and Tillage Research* **99**: 232–244. DOI: http://doi.org/10.1016/j.still.2008.02.001.

Massoud, EC, **Purdy, AJ**, **Miro, ME**, **Famiglietti, JS.** 2018. Projecting groundwater storage changes in California's Central Valley. *Scientific Reports* **8**: 12917. DOI: http://doi.org/10.1038/s41598-018-31210-1.

Mayak, S, **Tirosh, T**, **Glick, BR.** 2004. Plant growth-promoting bacteria that confer resistance to water stress in tomatoes and peppers. *Plant Science* **166**: 525–530. DOI: http://doi.org/10.1016/j.plantsci.2003.10.025.

McCallum, MH, **Kirkegaard, JA**, **Green, TW**, **Cresswell, HP**, **Davies, SL**, **Angus, JF**, **Peoples, MB.** 2004. Improved subsoil macroporosity following perennial pastures. *Australian Journal of Experimental Agriculture* **44**: 299. DOI: http://doi.org/10.1071/EA03076.

McDaniel, MD, **Grandy, AS**, **Tiemann, LK**, **Weintraub, MN.** 2016. Eleven years of crop diversification alters decomposition dynamics of litter mixtures incubated with soil. *Ecosphere* **7**(8): e01426. DOI: http://doi.org/10.1002/ecs2.1426.

Meier, J, **Zabel, F**, **Mauser, W.** 2018. A global approach to estimate irrigated areas—A comparison between different data and statistics. *Hydrology and Earth System Sciences* **22**: 1119–1133. DOI: http://doi.org/10.5194/hess-22-1119-2018.

Meurer, K, **Barron, J**, **Chenu, C**, **Coucheney, E**, **Fielding, M**, **Hallett, P**, **Herrmann, AM**, **Keller, T**, **Koestel, J**, **Larsbo, M**, **Lewan, E**, **Or, D**, **Parsons, D**, **Parvin, N**, **Taylor, A**, **Vereecken, H**, **Jarvis, N.** 2020. A framework for modelling soil structure dynamics induced by biological activity. *Global Change Biology* **26**: 5382–5403. DOI: http://doi.org/10.1111/gcb.15289.

Meyer, N, **Bergez, J-E**, **Constantin, J**, **Justes, E.** 2019. Cover crops reduce water drainage in temperate climates: A meta-analysis. *Agronomy for Sustainable Development* **39**: 3. DOI: http://doi.org/10.1007/s13593-018-0546-y.

Minasny, B, **McBratney, AB.** 2018. Limited effect of organic matter on soil available water capacity. *European Journal of Soil Science* **69**: 39–47. DOI: http://doi.org/10.1111/ejss.12475.

Mitchell, J, **Harben, R**, **Sposito, G**, **Shrestha, A**, **Munk, D**, **Miyao, G**, **Southard, R**, **Ferris, H**, **Horwath, WR**, **Kueneman, E**, **Fisher, J**, **Bottens, M**, **Hogan, P**, **Roy, R**, **Komar, J**, **Beck, D**, **Reicosky, D**, **Leinfelder-miles, M**, **Aegerter, B**, **Six, J**, **Giacomazzi, D**, **Sano, A**, **Sanchez, J**, **Crowell, M**, **Diener, J**,

Cordova, D, **Cordova, T**, **Rossiter, J**. 2016. Conservation agriculture: Systems thinking for sustainable farming. *California Agriculture* **70**: 53–57. DOI: https://doi.org/10.3733/ca.v070n02p53.

Mitchell, JP, **Shrestha, A**, **Irmak, S.** 2015. Trade-offs between winter cover crop production and soil water depletion in the San Joaquin Valley, California. *Journal of Soil and Water Conservation* **70**: 430–440. DOI: http://doi.org/10.2489/jswc.70.6.430.

Mitchell, JP, **Singh, PN**, **Wallender, WW**, **Munk, DS**, **Wroble, JF**, **Horwath, WR**, **Hogan, P**, **Roy, R**, **Hanson, BR.** 2012. No-tillage and high-residue practices reduce soil water evaporation. *California Agriculture* **66**: 55–61. DOI: http://doi.org/10.3733/ca.v066n02p55.

Moreno-Espíndola, IP, **Ferrara-Guerrero, MJ**, **Luna-Guido, ML**, **Ramírez-Villanueva, DA**, **De León-Lorenzana, AS**, **Gómez-Acata, S**, **González-Terreros, E**, **Ramírez-Barajas, B**, **Navarro-Noya, YE**, **Sánchez-Rodríguez, LM**, **Fuentes-Ponce, M**, **Macedas-Jímenez, JU**, **Dendooven, L.** 2018. The bacterial community structure and microbial activity in a traditional organic milpa farming system under different soil moisture conditions. *Frontiers in Microbiology* **9**: 2737. DOI: http://doi.org/10.3389/fmicb.2018.02737.

Morris, KS, **Bucini, G.** 2016. California's drought as opportunity: Redesigning U.S. agriculture for a changing climate. *Elementa: Science of the Anthropocene* **4**: 000142. DOI: http://doi.org/10.12952/journal.elementa.000142.

Mosquera, GM, **Crespo, P**, **Breuer, L**, **Feyen, J**, **Windhorst, D.** 2020. Water transport and tracer mixing in volcanic ash soils at a tropical hillslope: A wet layered sloping sponge. *Hydrological Processes* **34**: 2032–2047. DOI: http://doi.org/10.1002/hyp.13733.

Msigwa, A, **Chawanda, CJ**, **Komakech, HC**, **Nkwasa, A**, **van Griensven, A.** 2022. Representation of seasonal land use dynamics in SWAT+ for improved assessment of blue and green water consumption. *Hydrology and Earth System Sciences* **26**: 4447–4468. DOI: http://doi.org/10.5194/hess-26-4447-2022.

Munkholm, LJ, **Heck, RJ**, **Deen, B.** 2013. Long-term rotation and tillage effects on soil structure and crop yield. *Soil and Tillage Research* **127**: 85–91. DOI: http://doi.org/10.1016/j.still.2012.02.007.

Nabhan, GP, **McKibben, B.** 2013. *Growing food in a hotter, drier land: Lessons from desert farmers on adapting to climate uncertainty.* Chelsea, VT: Chelsea Green Pub.

Naseem, H, **Bano, A.** 2014. Role of plant growth-promoting rhizobacteria and their exopolysaccharide in drought tolerance of maize. *Journal of Plant Interactions* **9**: 689–701. DOI: http://doi.org/10.1080/17429145.2014.902125.

Naveed, M, **Mitter, B**, **Reichenauer, TG**, **Wieczorek, K**, **Sessitsch, A.** 2014. Increased drought stress resilience of maize through endophytic colonization by *Burkholderia phytofirmans* PsJN and *Enterobacter* sp. FD17. *Environmental and Experimental Botany* **97**: 30–39. DOI: http://doi.org/10.1016/j.envexpbot.2013.09.014.

Ngumbi, E, **Kloepper, J.** 2016. Bacterial-mediated drought tolerance: Current and future prospects. *Applied Soil Ecology* **105**: 109–125. DOI: http://doi.org/10.1016/j.apsoil.2016.04.009.

Nichols, R. 2015. USDA: A hedge against drought: Why healthy soil is "water in the bank." Available at https://www.usda.gov/media/blog/2015/05/12/hedge-against-drought-why-healthy-soil-water-bank. Accessed 01 February 2022.

Nichols, V, **Verhulst, N**, **Cox, R**, **Govaerts, B.** 2015. Weed dynamics and conservation agriculture principles: A review. *Field Crops Research* **183**: 56–68. DOI: http://doi.org/10.1016/j.fcr.2015.07.012.

Nielsen, DC, **Vigil, MF.** 2005. Legume green fallow effect on soil water content at wheat planting and wheat yield. *Agronomy Journal* **97**: 684–689. DOI: http://doi.org/10.2134/agronj2004.0071.

Niles, MT, **Hammond Wagner, CR.** 2019. The carrot or the stick? Drivers of California farmer support for varying groundwater management policies. *Environmental Research Communications* **1**: 045001. DOI: http://doi.org/10.1088/2515-7620/ab1778.

Niswonger, RG, **Morway, ED**, **Triana, E**, **Huntington, JL.** 2017. Managed aquifer recharge through off-season irrigation in agricultural regions. *Water Resources Research* **53**: 6970–6992. DOI: http://doi.org/10.1002/2017WR020458.

Nouri, H, **Chavoshi Borujeni, S**, **Hoekstra, AY.** 2019a. The blue water footprint of urban green spaces: An example for Adelaide, Australia. *Landscape and Urban Planning* **190**: 103613. DOI: http://doi.org/10.1016/j.landurbplan.2019.103613.

Nouri, H, **Stokvis, B**, **Galindo, A**, **Blatchford, M**, **Hoekstra, AY.** 2019b. Water scarcity alleviation through water footprint reduction in agriculture: The effect of soil mulching and drip irrigation. *Science of The Total Environment* **653**: 241–252. DOI: http://doi.org/10.1016/j.scitotenv.2018.10.311.

Nunes, MR, **Karlen, DL**, **Denardin, JE**, **Cambardella, CA.** 2019. Corn root and soil health indicator response to no-till production practices. *Agriculture, Ecosystems & Environment* **285**: 106607. DOI: http://doi.org/10.1016/j.agee.2019.106607.

Nziguheba, G, **Palm, CA**, **Berhe, T**, **Denning, G**, **Dicko, A**, **Diouf, O**, **Diru, W**, **Flor, R**, **Frimpong, F**, **Harawa, R**, **Kaya, B**, **Manumbu, E**, **McArthur, J**, **Mutuo, P**, **Ndiaye, M**, **Niang, A**, **Nkhoma, P**, **Nyadzi, G**, **Sachs, J**, **Sullivan, C**, **Teklu, G**, **Tobe, L**, **Sanchez, PA.** 2010. The African Green Revolution, in *Advances in agronomy.* Amsterdam, the Netherlands: Elsevier: 75–115. DOI: http://doi.org/10.1016/B978-0-12-385040-9.00003-7.

O'Brien, PL, **Daigh, ALM.** 2019. Tillage practices alter the surface energy balance—A review. *Soil and Tillage Research* **195**: 104354. DOI: http://doi.org/10.1016/j.still.2019.104354.

O'Geen, AT, **Saal, M**, **Dahlke, H**, **Doll, D**, **Elkins, R**, **Fulton, A**, **Fogg, G**, **Harter, T**, **Hopmans, JW**, **Ingels, C**, **Niederholzer, F**, **Solis, SS**, **Verdegaal, P**, **Walkinshaw, M.** 2015. Soil suitability index identifies potential areas for groundwater banking on agricultural lands. *California Agriculture* **69**: 75–84. DOI: http://doi.org/10.3733/ca.v069n02p75.

Oehl, F, **Sieverding, E**, **Mäder, P**, **Dubois, D**, **Ineichen, K**, **Boller, T**, **Wiemken, A.** 2004. Impact of long-term conventional and organic farming on the diversity of arbuscular mycorrhizal fungi. *Oecologia* **138**: 574–583. DOI: http://doi.org/10.1007/s00442-003-1458-2.

Ostrom, E. 1990. *Governing the commons: The evolution of institutions for collective action*. Cambridge, MA: Cambridge University Press.

Pahlavan-Rad, MR, **Dahmardeh, K**, **Hadizadeh, M**, **Keykha, G**, **Mohammadnia, N**, **Gangali, M**, **Keikha, M**, **Davatgar, N**, **Brungard, C.** 2020. Prediction of soil water infiltration using multiple linear regression and random forest in a dry flood plain, eastern Iran. *CATENA* **194**: 104715. DOI: http://doi.org/10.1016/j.catena.2020.104715.

Parihar, CM, **Nayak, HS**, **Rai, VK**, **Jat, SL**, **Parihar, N**, **Aggarwal, P**, **Mishra, AK.** 2019. Soil water dynamics, water productivity and radiation use efficiency of maize under multi-year conservation agriculture during contrasting rainfall events. *Field Crops Research* **241**: 107570. DOI: http://doi.org/10.1016/j.fcr.2019.107570.

Pathak, T, **Maskey, M**, **Dahlberg, J**, **Kearns, F**, **Bali, K**, **Zaccaria, D.** 2018. Climate change trends and impacts on California agriculture: A detailed review. *Agronomy* **8**: 25. DOI: http://doi.org/10.3390/agronomy8030025.

Paustian, K, **Andrén, O**, **Janzen, HH**, **Lal, R**, **Smith, P**, **Tian, G**, **Tiessen, H**, **Noordwijk, M**, **Woomer, PL.** 1997. Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use & Management* **13**: 230–244. DOI: http://doi.org/10.1111/j.1475-2743.1997.tb00594.x.

Pedranzani, H, **Rodríguez-Rivera, M**, **Gutiérrez, M**, **Porcel, R**, **Hause, B**, **Ruiz-Lozano, JM**. 2016. Arbuscular mycorrhizal symbiosis regulates physiology and performance of *Digitaria eriantha* plants subjected to abiotic stresses by modulating antioxidant and jasmonate levels. *Mycorrhiza* **26**: 141–152. DOI: http://doi.org/10.1007/s00572-015-0653-4.

Peng, Z, **Wang, L**, **Xie, J**, **Li, L**, **Coulter, JA**, **Zhang, R**, **Luo, Z**, **Cai, L**, **Carberry, P**, **Whitbread, A.** 2020. Conservation tillage increases yield and precipitation use efficiency of wheat on the semi-arid Loess Plateau of China. *Agricultural Water Management* **231**: 106024. DOI: http://doi.org/10.1016/j.agwat.2020.106024.

Peralta, AL, **Sun, Y**, **McDaniel, MD**, **Lennon, JT.** 2018. Crop rotational diversity increases disease suppressive capacity of soil microbiomes. *Ecosphere* **9**(5): e02235. DOI: http://doi.org/10.1002/ecs2.2235.

Perkons, U, **Kautz, T**, **Uteau, D**, **Peth, S**, **Geier, V**, **Thomas, K**, **Lütke Holz, K**, **Athmann, M**, **Pude, R**, **Köpke, U.** 2014. Root-length densities of various annual crops following crops with contrasting root systems. *Soil and Tillage Research* **137**: 50–57. DOI: http://doi.org/10.1016/j.still.2013.11.005.

Perry, C. 2007. Efficient irrigation; inefficient communication; flawed recommendations. *Irrigation and Drainage* **56**: 367–378. DOI: http://doi.org/10.1002/ird.323.

Peterson, CA, **Nunes, PA de A**, **Martins, AP**, **Bergamaschi, H**, **Anghinoni, I**, **Carvalho, PC de F**, **Gaudin, ACM.** 2019. Winter grazing does not affect soybean yield despite lower soil water content in a subtropical crop-livestock system. *Agronomy for Sustainable Development* **39**: 26. DOI: http://doi.org/10.1007/s13593-019-0573-3.

Poeplau, C, **Don, A.** 2015. Carbon sequestration in agricultural soils via cultivation of cover crops—A meta-analysis. *Agriculture, Ecosystems & Environment* **200**: 33–41. DOI: http://doi.org/10.1016/j.agee.2014.10.024.

Portmann, FT, **Siebert, S**, **Döll, P.** 2010. MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling: Monthly irrigated and rainfed crop areas. *Global Biogeochemical Cycles* **24**(1). DOI: http://doi.org/10.1029/2008GB003435.

Pretty, J, **Bharucha, ZP.** 2014. Sustainable intensification in agricultural systems. *Annals of Botany* **114**: 1571–1596. DOI: http://doi.org/10.1093/aob/mcu205.

Public Policy Institute of California. 2018. Water use in California. Available at https://www.ppic.org/publication/water-use-in-california/. Accessed 01 February 2022.

Püschel, D, **Bitterlich, M**, **Rydlová, J**, **Jansa, J.** 2020. Facilitation of plant water uptake by an arbuscular mycorrhizal fungus: A Gordian knot of roots and hyphae. *Mycorrhiza* **30**: 299–313. DOI: http://doi.org/10.1007/s00572-020-00949-9.

Quach, M, **Mele, PM**, **Hayden, HL**, **Marshall, AJ**, **Mann, L**, **Hu, H-W**, **He, J-Z.** 2022. Proximity to subsurface drip irrigation emitters altered soil microbial communities in two commercial processing tomato fields. *Applied Soil Ecology* **171**: 104315. DOI: http://doi.org/10.1016/j.apsoil.2021.104315.

Quinteiro, P, **Rafael, S**, **Villanueva-Rey, P**, **Ridoutt, B**, **Lopes, M**, **Arroja, L**, **Dias, AC.** 2018. A characterisation model to address the environmental impact of green water flows for water scarcity footprints. *Science of The Total Environment* **626**: 1210–1218. DOI: http://doi.org/10.1016/j.scitotenv.2018.01.201.

Rawls, WJ, **Pachepsky, YA**, **Ritchie, JC**, **Sobecki, TM**, **Bloodworth, H.** 2003. Effect of soil organic carbon on soil water retention. *Geoderma* **116**: 61–76. DOI: http://doi.org/10.1016/S0016-7061(03)00094-6.

Renwick, LLR, **Deen, W**, **Silva, L**, **Gilbert, ME**, **Maxwell, T**, **Bowles, TM**, **Gaudin, ACM.** 2021. Long-term crop rotation diversification enhances maize drought resistance through soil organic matter. *Environmental Research Letters* **16**: 084067. DOI: http://doi.org/10.1088/1748-9326/ac1468.

Richards, LA. 1931. Capillary conduction of liquids through porous mediums. *Physics* **1**: 318–333. DOI: http://doi.org/10.1063/1.1745010.

Rillig, MC, **Mummey, DL.** 2006. Mycorrhizas and soil structure. *New Phytologist* **171**: 41–53. DOI: http://doi.org/10.1111/j.1469-8137.2006.01750.x.

Rockström, J, **Falkenmark, M**, **Karlberg, L**, **Hoff, H**, **Rost, S**, **Gerten, D.** 2009. Future water availability for global food production: The potential of green water for increasing resilience to global change: Water availability for food production. *Water Resources Research* **45**(7). DOI: http://doi.org/10.1029/2007WR006767.

Rost, S, **Gerten, D**, **Bondeau, A**, **Lucht, W**, **Rohwer, J**, **Schaphoff, S.** 2008. Agricultural green and blue water consumption and its influence on the global water system: Global water use in agriculture. *Water Resources Research* **44**. DOI: http://doi.org/10.1029/2007WR006331.

Rubin, RL, **van Groenigen, KJ**, **Hungate, BA.** 2017. Plant growth promoting rhizobacteria are more effective under drought: A meta-analysis. *Plant Soil* **416**: 309–323. DOI: http://doi.org/10.1007/s11104-017-3199-8.

Sánchez, PA. 2010. Tripling crop yields in tropical Africa. *Nature Geoscience* **3**: 299–300. DOI: http://doi.org/10.1038/ngeo853.

Saxton, KE, **Rawls, WJ.** 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal* **70**: 1569–1578. DOI: http://doi.org/10.2136/sssaj2005.0117.

Scanlon, BR, **Zhang, Z**, **Reedy, RC**, **Pool, DR**, **Save, H**, **Long, D**, **Chen, J**, **Wolock, DM**, **Conway, BD**, **Winester, D.** 2015. Hydrologic implications of GRACE satellite data in the Colorado River Basin. *Water Resources Research* **51**: 9891–9903. DOI: http://doi.org/10.1002/2015WR018090.

Schjønning, P, **Thomsen, IK**, **Petersen, SO**, **Kristensen, K**, **Christensen, BT.** 2011. Relating soil microbial activity to water content and tillage-induced differences in soil structure. *Geoderma* **163**: 256–264. DOI: http://doi.org/10.1016/j.geoderma.2011.04.022.

Schmidt, JE, **Gaudin, ACM.** 2017. Toward an integrated root ideotype for irrigated systems. *Trends in Plant Science* **22**: 433–443. DOI: http://doi.org/10.1016/j.tplants.2017.02.001.

Schmidt, JE, **Peterson, C**, **Wang, D**, **Scow, KM**, **Gaudin, ACM**. 2018. Agroecosystem tradeoffs associated with conversion to subsurface drip irrigation in organic systems. *Agricultural Water Management* **202**: 1–8. DOI: https://doi.org/10.1016/j.agwat.2018.02.005.

Schwartz, RC, **Baumhardt, RL**, **Evett, SR.** 2010. Tillage effects on soil water redistribution and bare soil evaporation throughout a season. *Soil and Tillage Research* **110**: 221–229. DOI: http://doi.org/10.1016/j.still.2010.07.015.

Schwen, A, **Bodner, G**, **Scholl, P**, **Buchan, GD**, **Loiskandl, W.** 2011. Temporal dynamics of soil hydraulic properties and the water-conducting porosity under different tillage. *Soil and Tillage Research* **113**: 89–98. DOI: http://doi.org/10.1016/j.still.2011.02.005.

Sears, L, **Caparelli, J**, **Lee, C**, **Pan, D**, **Strandberg, G**, **Vuu, L**, **Lin Lawell, C-Y.** 2018. Jevons' paradox and efficient irrigation technology. *Sustainability* **10**: 1590. DOI: http://doi.org/10.3390/su10051590.

Siebert, S, **Burke, J**, **Faures, JM**, **Frenken, K**, **Hoogeveen, J**, **Döll, P**, **Portmann, FT.** 2010. Groundwater use for irrigation—A global inventory. *Hydrology and Earth System Science* **14**: 1863–1880. DOI: http://doi.org/10.5194/hess-14-1863-2010.

Šimůnek, J, **Genuchten, MTh**. 2008. Modeling nonequilibrium flow and transport processes using HYDRUS. *Vadose Zone Journal* **7**: 782–797. DOI: http://doi.org/10.2136/vzj2007.0074.

Šimůnek, J, **Genuchten, MTh**, **Šejna, M.** 2016. Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone Journal* **15**: 1–25. DOI: http://doi.org/10.2136/vzj2016.04.0033.

Six, J, **Elliott, ET**, **Paustian, K.** 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. *Soil Science Society of America Journal* **63**: 1350–1358. DOI: http://doi.org/10.2136/sssaj1999.6351350x.

Smith, CW. 2016. *Effects of implementation of soil health management practices on infiltration, saturated hydraulic conductivity and runoff.* USDA Natural Resources Conservation Service, National Soil Survey Center.

Smith, SE, **Read, DJ.** 2010. *Mycorrhizal symbiosis*. Cambridge, MA: Academic Press.

Soane, BD, **Ball, BC**, **Arvidsson, J**, **Basch, G**, **Moreno, F**, **Roger-Estrade, J.** 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil and Tillage Research* **118**: 66–87. DOI: http://doi.org/10.1016/j.still.2011.10.015.

Sofo, A, **Mininni, AN**, **Ricciuti, P.** 2020. Soil Macrofauna: A key factor for increasing soil fertility and promoting sustainable soil use in fruit orchard agrosystems. *Agronomy* **10**: 456. DOI: http://doi.org/10.3390/agronomy10040456.

Somers, E, **Vanderleyden, J**, **Srinivasan, M.** 2004. Rhizosphere bacterial signalling: A love parade beneath our feet. *Critical Reviews in Microbiology* **30**: 205–240. DOI: http://doi.org/10.1080/10408410490468786.

Sposito, G. 2013. Green water and global food security. *Vadose Zone Journal* **12**. DOI: http://doi.org/10.2136/vzj2013.02.0041.

Steffen, W, **Richardson, K**, **Rockstrom, J**, **Cornell, SE**, **Fetzer, I**, **Bennett, EM**, **Biggs, R**, **Carpenter, SR**, **de Vries, W**, **de Wit, CA**, **Folke, C**, **Gerten, D**, **Heinke, J**, **Mace, GM**, **Persson, LM**, **Ramanathan, V**,

Reyers, B, **Sorlin, S.** 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* **347**: 1259855. DOI: http://doi.org/10.1126/science.1259855.

Steudle, E. 2001. The cohesion-tension mechanism and the acquisition of water by plant roots. *Annual Review of Plant Biology* **52**: 847–875.

Stirzaker, RJ, **Maeko, TC**, **Annandale, JG**, **Steyn, JM**, **Adhanom, GT**, **Mpuisang, T**. 2017. Scheduling irrigation from wetting front depth. *Agricultural Water Management* **179**: 306–313. DOI: https://doi.org/10.1016/j.agwat.2016.06.024.

Strudley, M, **Green, T**, **Ascoughii, J.** 2008. Tillage effects on soil hydraulic properties in space and time: State of the science. *Soil and Tillage Research* **99**: 4–48. DOI: http://doi.org/10.1016/j.still.2008.01.007.

Sun, C, **Ren, L.** 2014. Assessing crop yield and crop water productivity and optimizing irrigation scheduling of winter wheat and summer maize in the Haihe plain using SWAT model. *Hydrological Processes* **28**: 2478–2498. DOI: http://doi.org/10.1002/hyp.9759.

Sun, M, **Ren, A**, **Gao, Z**, **Wang, P**, **Mo, F**, **Xue, L**, **Lei, M.** 2018. Long-term evaluation of tillage methods in fallow season for soil water storage, wheat yield and water use efficiency in semiarid southeast of the Loess Plateau. *Field Crops Research* **218**: 24–32. DOI: http://doi.org/10.1016/j.fcr.2017.12.021.

Taylor, R, **Zilberman, D.** 2017. Diffusion of drip irrigation: The case of California. *Applied Economic Perspectives and Policy* **39**: 16–40. DOI: http://doi.org/10.1093/aepp/ppw026.

Thirkell, TJ, **Charters, MD**, **Elliott, AJ**, **Sait, SM**, **Field, KJ.** 2017. Are mycorrhizal fungi our sustainable saviours? Considerations for achieving food security. *Journal of Ecology* **105**: 921–929. DOI: http://doi.org/10.1111/1365-2745.12788.

Timmusk, S, **Abd El-Daim, IA**, **Copolovici, L**, **Tanilas, T**, **Kännaste, A**, **Behers, L**, **Nevo, E**, **Seisenbaeva, G**, **Stenström, E**, **Niinemets, Ü.** 2014. Drought-tolerance of wheat improved by Rhizosphere bacteria from harsh environments: Enhanced biomass production and reduced emissions of stress volatiles. *PLoS One* **9**: e96086. DOI: http://doi.org/10.1371/journal.pone.0096086.

Trenberth, KE, **Dai, A**, **van der Schrier, G**, **Jones, PD**, **Barichivich, J**, **Briffa, KR**, **Sheffield, J.** 2014. Global warming and changes in drought. *Nature Climate Change* **4**: 17–22. DOI: http://doi.org/10.1038/nclimate2067.

Trout, TJ, **Manning, DT.** 2019. An economic and biophysical model of deficit irrigation. *Agronomy Journal* **111**: 3182–3193. DOI: http://doi.org/10.2134/agronj2019.03.0209.

Turmel, M-S, **Speratti, A**, **Baudron, F**, **Verhulst, N**, **Govaerts, B.** 2015. Crop residue management and soil health: A systems analysis. *Agricultural Systems* **134**: 6–16. DOI: http://doi.org/10.1016/j.agsy.2014.05.009.

Unger, PW, **Vigil, MF.** 1998. Cover crop effects on soil water relationships. *Journal of Soil and Water Conservation* **53**: 200–207.

Van Gaelen, H. 2016. Evaluation of agricultural management from field to catchment scale: Development of a parsimonious agro-hydrological model [PhD thesis]. KU Leuven, Belgium.

Van Geel, M, **Verbruggen, E**, **De Beenhouwer, M**, **van Rennes, G**, **Lievens, B**, **Honnay, O.** 2017. High soil phosphorus levels overrule the potential benefits of organic farming on arbuscular mycorrhizal diversity in northern vineyards. *Agriculture, Ecosystems & Environment* **248**: 144–152. DOI: http://doi.org/10.1016/j.agee.2017.07.017.

Vardharajula, S, **Zulfikar Ali, S**, **Grover, M**, **Reddy, G**, **Bandi, V.** 2011. Drought-tolerant plant growth promoting *Bacillus* spp.: Effect on growth, osmolytes, and antioxidant status of maize under drought stress. *Journal of Plant Interactions* **6**: 1–14. DOI: http://doi.org/10.1080/17429145.2010.535178.

Veettil, AV, **Mishra, AK.** 2016. Water security assessment using blue and green water footprint concepts. *Journal of Hydrology* **542**: 589–602. DOI: http://doi.org/10.1016/j.jhydrol.2016.09.032.

Vercambre, G, **Pagès, L**, **Doussan, C**, **Habib, R.** 2003. Architectural analysis and synthesis of plum tree root system in an orchard using a quantitative modelling approach. *Plant and Soil* **251**: 1–11. DOI: http://doi.org/10.1023/A:1022961513239.

Vereecken, H, **Schnepf, A**, **Hopmans, JW**, **Javaux, M**, **Or, D**, **Roose, T**, **Vanderborght, J**, **Young, MH**, **Amelung, W**, **Aitkenhead, M**, **Allison, SD**, **Assouline, S**, **Baveye, P**, **Berli, M**, **Brüggemann, N**, **Finke, P**, **Flury, M**, **Gaiser, T**, **Govers, G**, **Ghezzehei, T**, **Hallett, P**, **Hendricks Franssen, HJ**, **Heppell, J**, **Horn, R**, **Huisman, JA**, **Jacques, D**, **Jonard, F**, **Kollet, S**, **Lafolie, F**, **Lamorski, K**, **Leitner, D**, **McBratney, A**, **Minasny, B**, **Montzka, C**, **Nowak, W**, **Pachepsky, Y**, **Padarian, J**, **Romano, N**, **Roth, K**, **Rothfuss, Y**, **Rowe, EC**, **Schwen, A**, **Šimůnek, J**, **Tiktak, A**, **Van Dam, J**, **van der Zee, SEATM**, **Vogel, HJ**, **Vrugt, JA**, **Wöhling, T**, **Young, IM.** 2016. Modeling soil processes: Review, key challenges, and new perspectives. *Vadose Zone Journal* **15**: vzj2015.09.0131. DOI: http://doi.org/10.2136/vzj2015.09.0131.

Villamil, MB, **Bollero, GA**, **Darmody, RG**, **Simmons, FW**, **Bullock, DG.** 2006. No-till corn/soybean systems including winter cover crops: Effects on soil properties. *Soil Science Society of America Journal* **70**: 1936–1944. DOI: http://doi.org/10.2136/sssaj2005.0350.

Vincent, C, **Rowland, D**, **Schaffer, B**, **Bassil, E**, **Racette, K**, **Zurweller, B.** 2020. Primed acclimation: A physiological process offers a strategy for more resilient and irrigation-efficient crop production. *Plant Science* **295**: 110240. DOI: http://doi.org/10.1016/j.plantsci.2019.110240.

von Korff, Y, **Daniell, KA**, **Moellenkamp, S**, **Bots, P**, **Bijlsma, RM.** 2012. Implementing participatory water management: Recent advances in theory, practice, and evaluation. *Equipment & Supply* **17**: art30. DOI: http://doi.org/10.5751/ES-04733-170130.

Vurukonda, SSKP, **Vardharajula, S**, **Shrivastava, M**, **SkZ, A.** 2016. Enhancement of drought stress tolerance in crops by plant growth promoting rhizobacteria. *Microbiological Research* **184**: 13–24. DOI: http://doi.org/10.1016/j.micres.2015.12.003.

Wade, J, **Beetstra, MA**, **Hamilton, ML**, **Culman, SW**, **Margenot, AJ.** 2021. Soil health conceptualization differs across key stakeholder groups in the Midwest. *Journal of Soil and Water Conservation* **76**(6): 527–533. DOI: http://doi.org/10.2489/jswc.2021.02158.

Wade, J, **Culman, SW**, **Logan, JAR**, **Poffenbarger, H**, **Demyan, MS**, **Grove, JH**, **Mallarino, AP**, **McGrath, JM**, **Ruark, M**, **West, JR.** 2020. Improved soil biological health increases corn grain yield in N fertilized systems across the Corn Belt. *Scientific Reports* **10**: 3917. DOI: http://doi.org/10.1038/s41598-020-60987-3.

Waqas, MS, **Cheema, MJM**, **Hussain, S**, **Ullah, MK**, **Iqbal, MM.** 2021. Delayed irrigation: An approach to enhance crop water productivity and to investigate its effects on potato yield and growth parameters. *Agricultural Water Management* **245**: 106576. DOI: http://doi.org/10.1016/j.agwat.2020.106576.

Ward, FA, **Pulido-Velazquez, M.** 2008. Water conservation in irrigation can increase water use. *Proceedings of the National Academy of Sciences* **105**: 18215–18220. DOI: http://doi.org/10.1073/pnas.0805554105.

Ward, PR, **Flower, KC**, **Cordingley, N**, **Weeks, C**, **Micin, SF.** 2012. Soil water balance with cover crops and conservation agriculture in a Mediterranean climate. *Field Crops Research* **132**: 33–39. DOI: http://doi.org/10.1016/j.fcr.2011.10.017.

Waterhouse, H, **Bachand, S**, **Mountjoy, D**, **Choperena, J**, **Bachand, P**, **Dahlke, H**, **Horwath, W.** 2020. Agricultural managed aquifer recharge—Water quality factors to consider. *California Agriculture* **74**: 144–154.

Weaver, JE, **Bruner, WE.** 1928. Root development of vegetable crops. *Nature* **121**: 53–53. DOI: http://doi.org/10.1038/121053a0.

White, JW, **Jones, JW**, **Porter, C**, **McMaster, S**, **Sommer, R.** 2010. Issues of spatial and temporal scale in modeling the effects of field operations on soil properties. *Operational Research: An International Journal* **10**: 279–299. DOI: http://doi.org/10.1007/s12351-009-0067-1.

Williams, A, **Hunter, MC**, **Kammerer, M**, **Kane, DA**, **Jordan, NR**, **Mortensen, DA**, **Smith, RG**, **Snapp, S**, **Davis, AS.** 2016. Soil water holding capacity mitigates downside risk and volatility in US Rainfed Maize: Time to invest in soil organic matter? *PLoS One* **11**: e0160974. DOI: http://doi.org/10.1371/journal.pone.0160974.

Williams, A, **Vries, FT**. 2020. Plant root exudation under drought: Implications for ecosystem functioning. *New Phytologist* **225**: 1899–1905. DOI: https://doi.org/10.1111/nph.16223.

Williams, SM, **Weil, RR.** 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. *Soil Science Society of America Journal* **68**: 1403–1409. DOI: http://doi.org/10.2136/sssaj2004.1403.

Xiong, P, **Zhang, Z**, **Peng, X**. 2022. Root and root derived biopore interactions in soils: A review. *Journal of Plant Nutrition and Soil Science* **185**: 643–655. DOI: https://doi.org/10.1002/jpln.202200003.

Zhang, D, **Chen, X**, **Yao, H**, **Lin, B.** 2015. Improved calibration scheme of SWAT by separating wet and dry seasons. *Ecological Modelling* **301**: 54–61. DOI: http://doi.org/10.1016/j.ecolmodel.2015.01.018.

Zhang, J, **Guan, K**, **Peng, B**, **Pan, M**, **Zhou, W**, **Jiang, C**, **Kimm, H**, **Franz, TE**, **Grant, RF**, **Yang, Y**, **Rudnick, DR**, **Heeren, DM**, **Suyker, AE**, **Bauerle, WL**, **Miner, GL.** 2021. Sustainable irrigation based on co-regulation of soil water supply and atmospheric evaporative demand. *Nature Communications* **12**: 5549. DOI: http://doi.org/10.1038/s41467-021-25254-7.

Zhang, Z, **Yan, L**, **Wang, Y**, **Ruan, R**, **Xiong, P**, **Peng, X**. 2022. Bio-tillage improves soil physical properties and maize growth in a compacted Vertisol by cover crops. *Soil Science Society of America Journal* **86**: 324–337. DOI: https://doi.org/10.1002/saj2.20368.

Zheng, W, **Zeng, S**, **Bais, H**, **LaManna, JM**, **Hussey, DS**, **Jacobson, DL**, **Jin, Y.** 2018. Plant Growth-Promoting Rhizobacteria (PGPR) reduce evaporation and increase soil water retention. *Water Resources Research* **54**: 3673–3687. DOI: http://doi.org/10.1029/2018WR022656.

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