Managing irrigation for soil health in irrigated arid and semi-arid regions

Jeffrey Peter Mitchell and Howard Ferris, University of California, Davis, USA; Anil Shrestha, California State University, Fresno, USA; Francis Larney, Agriculture and Agri-Food Canada, Canada; and Garrison Sposito, University of California, Berkeley, USA

1 Introduction

Recent concern about the continuing ability of soils to provide ecosystem services essential for food security (Amundson et al., 2015) has given considerable importance to the concept of soil health (Karlen, 2012; CDFA, 2016; FAO, 2017) advocated by the United Nations Food and Agriculture Organization, United States Department of Agriculture Natural Resources Conservation Service and California Department of Food and Agriculture, among many other regional and local organizations. In the upcoming three decades, the global demand for food is expected to double because of increasing population and per capita income, while agricultural resources, such as water for irrigation and arable land, are projected to become even more constrained and scarce (Tilman et al., 2011; Foley et al., 2011; Sposito, 2013; Jägermeyr et al., 2016). Maintaining soil health in the face of this increasing demand for food and increasing pressure on agricultural resources is thus seen as one of the major challenges of the twenty-first century (Foley et al., 2011; Hall, 2014). Managing water to optimize soil health in the world's irrigated regions is critical to meeting these challenges.

One response to this challenge has been a call for sustainable intensification, that is, increasing the quantity of food produced per unit of input resource without undermining

http://dx.doi.org/10.19103/AS.2017.0033.24

the ability of soils to deliver the ecosystem services necessary to meet future food demand (Foley et al., 2011; Garnett et al., 2013). However, soil health management that can be reliably and flexibly applied under a variety of climatic and soil conditions is needed in order to achieve this goal (Foley et al., 2011; Giller et al., 2015). Because of the fundamental role carbon (C) plays in soil ecosystem functions (Reicosky, 2003; Palm et al., 2007; Franzluebbers, 2010; Delgado et al., 2011; Sposito, 2016), soil health management has often been directly linked to soil C management and the associated goal of increasing the C content of soils (Feger and Hawtree, 2013; CDFA, 2016). Key management principles for increasing soil C content and, therefore, soil health include managing irrigation water, minimizing soil disturbance, maximizing surface plant cover and stimulating subsurface biological activity (Franzluebbers, 2010; Lal, 2013; Reicosky, 2015; Sposito, 2014; CDFA, 2016). These principles are assumed to be universal in that they can be applied effectively through regionally appropriate practices across diverse climatic environments.

However, because the relationship between soil properties and soil ecosystem functions is not completely understood (Wall, 2013) and incomplete evidence exists as to whether the 'systematic bias' towards soils with higher soil organic matter will actually lead to healthier soils (Castro and Hartz, 2016), there is an ongoing debate over the role of soil health management in science-based agriculture. There is also some uncertainty regarding the extent to which managing soil health for sustainable intensification can be achieved successfully across diverse climatic environments, in particular, arid and semi-arid environments (Sojka and Upchurch, 1999; Bouma, 2009; Mitchell et al., 2017). To what extent, for instance, can soil health management practices that have been proven effective in other regions be adapted and applied with benefit to arid and semi-arid regions? The present chapter addresses this overarching question by summarizing recent information on the application of soil health management principles in irrigated and dry land arid and semi-arid environments, including examples of cost–benefit trade-offs associated with reduced-disturbance no-tillage systems and the use of cover crops.

2 Arid and semi-arid regions

Hyper-arid, arid and semi-arid regions, also termed dry lands, occupy almost 40% of the terrestrial land surface, are home for at least 20% of the world population, nearly all residing in developing nations and, when irrigated, account for around 40% of the global crop production (Wang et al., 2012) (Fig. 1). These regions are characterized climatologically by the ratio, P/ETo and the aridity index (AI), where P is the precipitation, and ETo is the potential evapotranspiration (Wang et al., 2012). Hyper-arid zones have AI < 0.05, with infrequent and highly irregular rainfall totalling below 100 mm annually. Arid zones have 0.05 < AI < 0.20 and can be farmed only with irrigation, with their annual rainfall being between 100 and 300 mm. Semi-arid zones have 0.20 < AI < 0.50 and can support rainfed agriculture, with annual rainfall ranging between 300 and 500 mm. Precipitation in these three regions varies annually within the very broad range of –50 to +200% of the mean value (Stewart and Peterson, 2015) and it occurs seasonally, usually either during summer or winter. Semi-arid regions of California, for instance, receive precipitation during winter, whereas areas of eastern Africa and the Central Great Plains area of North America have dry winters and wet summers. Average annual ETo for California's highly productive Central Valley is about 1430 mm, while the region's annual precipitation is

Figure 1 Arid and semi-arid regions of the world, modified with permission from UN Decade for deserts and the fight against desertification (http://www.un.org/en/events/desertification_decade/index.shtml).

only 100–450 mm (http://wwwcimis.water.ca.gov/App_Themes/images/etozonemap.jpg). Since these regions are drought-prone, managing water resources by conservation and efficient use throughout the year is a requirement for and a major challenge to agricultural production (Wallace, 2000; Hsiao, 2007; Stewart and Peterson, 2015). Irrigated arid and semi-arid agricultural regions are found in all continents and cover both developed and developing countries (http://www.fao.org/ag/agl/aglw/aquastat/irrigationmap/index.stm), with particularly high percentages of total land area in the Great Plains and western USA, India, China, southeastern Australia and throughout the Middle East.

In most dry lands, there is a very limited likelihood of substantially increasing the amount of water currently withdrawn for use in irrigated agriculture. To meet future challenges, it is important to optimize water use efficiency in these regions through systematic approaches (Wallace, 2000; Hsiao, 2007; Chukalla et al., 2015; Barron et al., 2015; Jägermeyr et al., 2016). In addition, it is increasingly recognized that although soil has been an under-appreciated component of water management, it must now become more central to policies and practices in order to ensure its effectiveness in the capture and retention of water to maximize the availability at the times and places it is required (Wallace, 2000; Bettner et al., 2012; Stewart and Peterson, 2015; Chukalla et al., 2015). It is well known that soils which managed to maintain or increase their C content to improve soil health (CDFA, 2016) show improved infiltration characteristics, as well as greater water storage capacities, through the well-known positive effects of organic matter on soil porosity and structure (Palm et al., 2007; Franzluebbers, 2010; Feger and Hawtree, 2013; CDFA, 2016). Thus, soil carbon management, although not yet widely emphasized in arid and semi-arid regions, can be viewed as a major management option to increase water use efficiency (Hudson, 1994; Rawls et al., 2003).

Current global assessments indicate that a large fraction of water consumed by agricultural production in arid and semi-arid zones is actually used quite inefficiently due to the losses associated with runoff, soil evaporation and deep percolation (Brauman et al., 2013). Therefore, a major goal is to increase the productive flow of soil water, that is,

increase its consumption by crop transpiration and reduce its loss by runoff, evaporation and deep percolation, through some practices that maximize both water infiltration into soil and soil water retention (Röckstrom and Falkenmark, 2000; Wallace, 2000; Franzluebbers, 2010; Kirkegaard and Hunt, 2010). This goal may be accomplished through applying the three fundamental soil health management principles: minimize soil disturbance, increase plant diversity and keep soil covered (Klocke et al., 2009; FAO, 2017; Mitchell et al., 2017).

For instance, no-till and cover crop management techniques applied for 17 years at the Conservation Agriculture Systems Project, located in the San Joaquín Valley (CA, USA), have resulted in the soil C content to more than double at the 0–15 cm depth when compared to standard-tillage no cover crop management (Mitchell et al., 2017). In addition, 24 mm more water was retained in the soil following wheat silage harvest and before corn seeding under no-tillage management as compared with tilled soil (Mitchell et al., 2012). Assuming a seasonal evapotranspiration demand of 760 mm, Mitchell et al. (2012) estimated that no-till management combined with high surface residue coverage could reduce soil evaporation losses by up to 100 mm, or about 13% of the estimated seasonal crop ET demand (Mitchell et al., 2012). Surface crop residues reduce the evaporation of water from soil by shading, lowering the surface soil temperature and reducing the wind effects (Klocke et al., 2009; van Donk et al. 2010). In regions of the world where such practices are common – Brazil, Argentina, Paraguay, Canada, Western Australia, the Dakotas and Nebraska in the United States – generating and preserving surface residues while reducing soil disturbance are integral parts of soil health management and primary components of sustainable agricultural production (Crovetto, 1996, 2006; Junior et al., 2012). For instance, at Kansas State University's Southwest Research and Extension Center (Garden City, KS, USA), full-surface residue coverage with corn (*Zea mays* L.) stover and wheat (*Triticum aestivum* L.) stubble has been shown to reduce soil evaporation by 50–65% as compared to bare soil without shading (Klocke et al., 2009). Significant reductions in soil evaporation resulting from organic surface mulching were also reported by Chukalla et al. (2015) in a comprehensive simulation study using the AquaCrop model. Decreasing soil water loss by evaporation may thus be not only a means for increasing water use efficiency, but also for maintaining the soil food web in a biologically active state (Ferris et al., 2004), which can in turn contribute to improving soil health in irrigated arid and semi-arid regions.

3 No-till cropping systems

The use of fallow periods to capture and store water in soil for subsequent cropping is a common practice in many dry lands (Verburg et al., 2012; Stewart and Peterson, 2015). Dry lands in which fallowing is routinely followed have benefited from no-till residue retention practices as means of diversifying and intensifying crop production. For instance, the adoption and consistent use of no-till management practices throughout the vast Canadian prairie in Alberta, Saskatchewan and Manitoba provinces, beginning in the 1990s, has reduced the reliance on the traditional summer fallow, enhanced soil health, increased soil water availability in near-surface layers (Larney et al., 2004; Larney and Lindwall, 1995) and permitted the introduction of new crops, including oilseeds and legumes (Larney and Lindwall, 1995). Also, there is evidence that no-till management itself has improved, becoming more reliable in recent years, and that changes in soil

properties under no-till cropping tend to be positive (Smith et al., 2012). No-till, in fact, has become the recommended cropping system throughout this region. As an example, no-till agriculture in Alberta, Canada, increased from about 5% of the seeded area in 1991 to over 80% by 2011. A comprehensive history of the development of no-till cropping systems in the Canadian prairie has been compiled by Lindwall and Sonntag (2010).

In the Central Great Plains (USA), no-till has also impacted agricultural management, permitting both the intensification and the diversification of cropping by initiating what has been termed 'a spiral of soil regeneration where interactions among more favourable water relations, residue production and crop yield are continually improving soil health and, consequently, future crop performance' (Anderson, 2011). No-till cropping has also been extensively adopted for cereal production in the dry lands of southwestern Australia (Ward et al., 2012). In this region, the benefits of surface residues include increased availability of soil water during germination and early growth of the subsequent crop (K. Flowers, pers. comm.). Harvesting techniques that retain tall-standing crop residues in combination with adequate horizontal residue coverage optimize water capture (Swell et al., 2015). Verburg et al. (2012) concluded from their field and lysimeter experiments and simulations that the role of fallow management in accumulating soil water for subsequent cropping could, in some cases, account for up to 45 mm of reduced evaporation losses under high-residue levels, and could be even more important than either genetic or in-crop improvements. The conservation of soil moisture as well as improved soil structure and soil health has been reported as a major impetus for increased adoption of no-till practices in Australia (Scott et al., 2013).

Such benefits of residue retention and no-till management have not been seen, however, in the Mediterranean climate region of the Pacific Northwest, USA, which has high winter precipitation and low summer rainfall (Wuest and Schillinger, 2011). In this dry land region, the over-summer seed-zone water loss under no-till fallow is greater than that under tillage fallow. Evidently, the surface soil mulch that results from tilled summer fallow insulates against heat flow downwards during the day in early summer. The tilled soil mulch also reduces water movement to the soil surface from depth. Thus, the system works to keep a high-water-content seed zone within the reach of a deep furrow drill, usually until fall (Wuest and Shillinger, 2011). In the Pacific Northwest, no-till rarely results in adequate seed-zone water content relative to tilled summer fallow, underscoring once again the importance of crop management that respects both the timing and the frequency of precipitation in dry lands (Wuest, 2010).

4 Cover cropping systems

Cover crop management techniques bring demonstrable soil health benefits to agricultural systems (Snapp et al., 2005; Schipanski et al., 2014; Poeplau and Don, 2015; Mitchell et al., 2017). They increase soil C content (Popelau and Don, 2015) along with other nutrients (Creamer and Baldwin, 2000) and, if cover crop residues are used as mulch instead of being incorporated as green manure, they cool the soil surface while reducing soil water evaporation. There is, however, very limited information on cover crop water demand, especially in arid and semi-arid climates. DeLaune et al. (2015), working under the exceptional drought conditions that Texas (USA) has experienced in recent years, found that soil infiltration properties may be enhanced by certain cover crop mixtures sufficiently

to offset or reduce soil water losses from cover crop demand. Prichard (1989) in California evaluated year-long cover cropping and found that (i) cover crop water use varied according to specific species mixtures, (ii) seasonal water use by cover crop mixtures ranged from 96 to 136% of that of the residual-herbicide control and (iii) when used in surface mulches, cover crop water use may be similar to that of residual herbicide and chemical mowing controls. Another research in California (Mitchell et al., 1999, 2015a) indicates soil water depletion from 0 to 90 cm depth was on the order of 50 to 70 mm greater in cover-cropped versus winter-fallowed soils in mid-March, at the time of cover crop termination, relative to water storage in fallow soils over three years. Thus, an investment of irrigation water to establish and augment winter precipitation in no-tillage, high-residue production systems in this region may be warranted as a means for adding residues, increasing soil carbon and enhancing soil health when the combined water conservation aspects of the overall production system are considered (Mitchell et al., 2012).

In the semi-arid Mediterranean climate of Western Australia, with hot, dry summers, cover cropping with surface residue retention had a limited impact on the total evaporation during the summer and fall periods (Ward et al., 2012). Because of the high potential evapotranspiration and low precipitation during the summer in Australia, cover crops converted to surface mulch did not result in greater soil water retention and did not have major impact on the water balance. Any benefits of the cover crop residues, in fact, lasted only a few days after summer rainfall (Ward et al., 2012).

The amount of aboveground biomass that is produced by intercrop winter cover crops in semi-arid zones depends on a number of factors, including rainfall and irrigation amounts as well as timing and the specific cover crop species mixture used. In a long-term study (17 years) conducted in the San Joaquín Valley (Mitchell et al., 2015b), a total of 64.6 MT ha^{-1} (annual average, 3.8 Mg ha^{-1}) aboveground rye (*Secale cereale*), triticale and faba bean (*Vicia faba*) cover crop biomass was produced (Fig. 2) with an average annual precipitation (October–April) of 160 mm, but also with a range of annual amounts from 64 to 434 mm. There was, however, a large variability in the annual biomass produced due to variability in water inputs, ranging from 0.039 Mg ha^{-1} during the 2006–2007 winter, with very little rainfall (88 mm), to 9.34 Mg ha^{-1} during the first winter, when 100 mm of irrigation water was applied initially. During the years when small volumes of irrigation water were applied (2000, 2013–2016), the cover crop growth exceeded the 17-year average. These results are consistent with the observations of Brennan and Boyd (2012) that, in dry lands, annual cover crop biomass varies considerably, with rainfall frequency and irrigation timing both playing critical roles.

Soil water depletion by winter cover crops (Fig. 3) in California tends not to be large because potential evapotranspiration during the winter cover crop growing season is much lower – only about 10% of that in mid-summer (Department of Water Resources, 2017), resulting in low cover crop transpiration. In addition, once the winter cover crop canopy is developed, it will shade and cool the soil surface, thereby further reducing soil water evaporation – 'taking the E out of ET' – and increasing water use efficiency by higher productive flow of soil water through the cover crop (D. Beck, pers. comm.). Furthermore, there is a speculation that a cover crop canopy, with its greater surface area than bare soil, may also aid in increased dew interception during damp winter mornings, which may also offset cover crop transpiration. The research by Mitchell et al. (2017) has recently documented that, over time, cover crops increase soil water infiltration, as also noted by Delaune et al. (2015), and can lead to greater capture of precipitation. Cover crops have also been used in the semi-arid regions of California (USA) as a means of

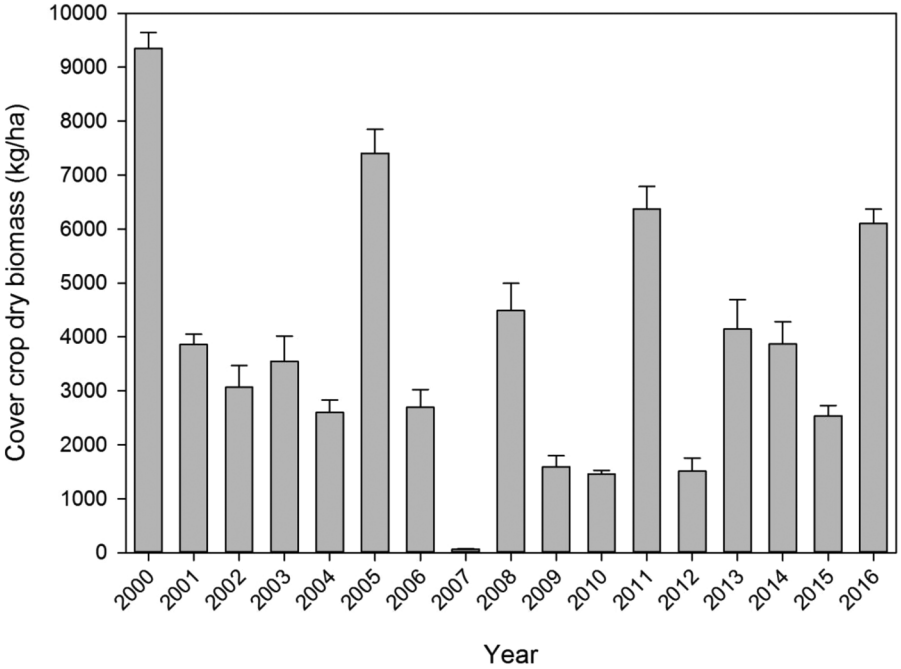

Figure 2 Cover crop biomass produced in the long-term study in Five Points, CA, USA.

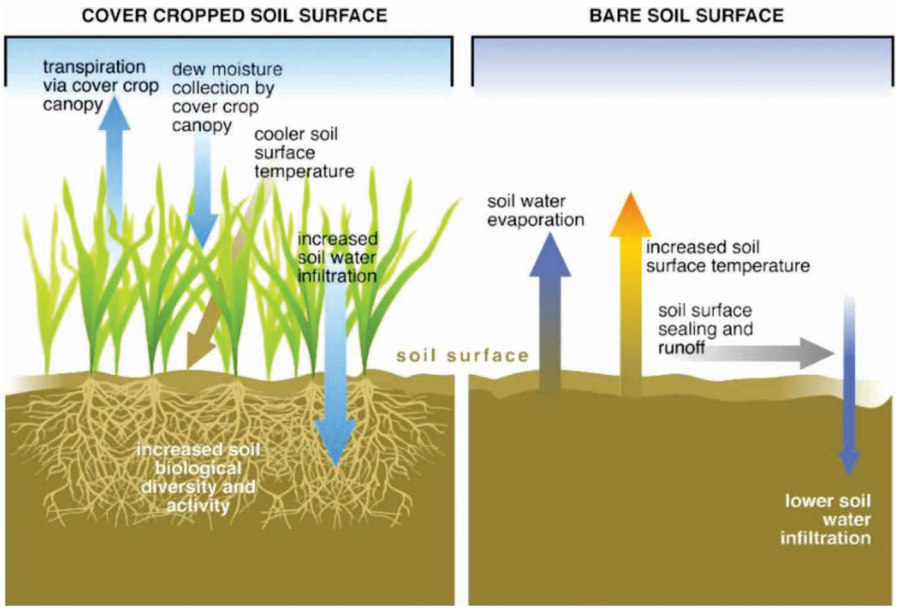

Figure 3 Possible mechanisms for water relations in cover cropping versus fallow systems.

improving soil health in the production of walnuts (*Juglans californica* S. Wats.) (R. Lester, pers. comm.), tomatoes (*Solanum lycopersicon*) (D. Ramos, pers. comm.), and almonds (*Prunus dulcis* Mill.) (S. Boone, pers. comm.). Similar evaluations of trade-offs between cover crop production and soil water depletion are underway in Australia (S. Groff, pers. comm.). In addition to conserving soil water by providing surface cover in semi-arid zones, cover crops play a role in soil health management by reducing wind and water erosion, scavenging excess leachable nitrate fertilizer from the shallow soil profile (Weinert et al., 2002) and suppressing weeds and harmful insects.

5 Soil food web management for nitrogen availability in arid and semi-arid areas

In conventional production systems in arid and semi-arid regions of most developed countries, nitrogen (N) and other plant nutrients are applied as mineral fertilizers prior to planting or early in the growing season (Ferri et al., 2004). Such approaches typically exceed plant requirements at the time of application; they can result in adverse effects on plants and on soil organisms, and in losses through leaching with rainfall or over irrigation or denitrification (Poudel et al., 2001; Joyce et al., 2002; Mosier et al., 2002). An alternative is to manage the soil food web so that it is active year round and can function to cycle and mineralize nutrient in greater synchrony with periods of crop demand. This requires the application of soil health management practices that minimize environmental constraints and limitations of resource availability. In the semi-arid Sacramento Valley of California, USA, Ferris et al. (2004) irrigated dry soil of late summer and provided carbon sources via cover crops to test whether grazing on bacteria and fungi by microbivorous nematodes in the spring increased N availability to the next crop. In general, maintaining the soil food web in a biologically active state during the fall with irrigation, when the soil would normally be dry, and without vegetation or cover, but warm enough for biological activity, enhanced N availability for the subsequent summer crop. Such soil health management approaches are not, however, widely used due to perceived uncertainties related to costs or trade-offs associated with diverting irrigation water from 'direct' crop requirements. However, the relatively small investments of water that might be required to establish cover crops to 'keep the soil biologically active' at key times within certain semi-arid regions suggest that the use of cover crops offers a wide range of management options to improve overall soil health. Additionally, reducing tillage can also contribute to increases in fungi, enhance the soil food web and result in accelerated soil C storage (Minoshima et al., 2007).

6 Conclusion

To meet the global food security challenge that is widely projected in the upcoming three decades, in light of ever more stringent resource constraints for agricultural production, water scarcity (Richter, 2016), declining rates of growth in crop yields (http://www.fao.org/wsfs/forum2050/wsfs-forum/en/), limited potential for cropland expansion (Lal, 2013; Alexandratos and Bruinsma, 2012) and climate change (Solomon et al., 2009), the food production must somehow increase by 70% (Alexandratos and Bruinsma, 2012).

Recognition of the enormity of this challenge has put 'soils back on the global agenda' (Bouma, 2009) as a vitally integral factor in our ability to ultimately and sustainably produce enough food for the world's population (Paustian et al., 2016). Increasingly, there are calls to 'radically rethink agriculture' (Federoff et al., 2010) and avoid extractive farming practices (Lal, 2013).

Taken together, the principles and practices that have been described in this chapter, namely no-tillage, residue retention and the use of cover crops, are part of what have been called 'conservation agriculture' (CA) systems (Lal, 2015). The potential benefits of CA systems, including reduced soil erosion, increased water use efficiency that may be achieved by higher soil water infiltration and retention and decreased soil water evaporation and enhanced soil biology, are particularly important in the irrigated arid and semi-arid areas that have been the emphasis of this chapter. While the rationale for the core principles of these CA systems (i.e. reducing soil degradation and production costs) has received considerable attention over the past two decades, more flexible and less dogmatic approaches to what has been termed 'systems agronomy' and the overall goals for sustainable production have also recently been urged (Giller et al., 2015). These urgings stem from two interrelated sources of concern or insights related to how CA systems are first of all defined, implemented and evaluated across diverse regions, and how they actually perform (Pittelkow et al., 2014; Stevenson et al., 2014), as well as how they have been promoted or, at times, been rather dogmatically prescribed (Giller et al., 2015). A detailed exposure of these concerns is beyond the scope of this review; however, it is important to note that the vigorous and at times acrimonious debate that has been undertaken about CA in recent years has been useful in focusing attention on what may be the best ideas for moving food production systems forward in all environments.

7 Future trends

There are many clear requirements for additional flexibly designed research in the arena of soil health management in arid and semi-arid regions and in recent years, there have been suggestions for what such research might look like. Giller (2015) and the internationally focused group based in Wageningen in the Netherlands have urged that a broader 'systems agronomy' approach be pursued rather than the 'dogmatic and prescriptive' emphasis of CA to overcome problems associated with continuous no-till such as 'soil compaction, excessive buildup of soil organic matter in the surface horizons and herbicide-resistant weeds'. Pittelkow et al. (2015) argued in a similar fashion for 'development and improvement of no-till crop management under various conditions across the globe' and this suggestion certainly has value in many parts of arid and semi-arid production regions where such approaches have not been attempted. Lal (2015) had eloquently called for soil stewardship and soil care to be 'embedded in every fruit and vegetable eaten, in each grain ground into the bread consumed, in every cup of water used, in every breath of air inhaled and in every scenic landscape cherished', and that these goals may be realized through the development of an appropriate package of farm operations and cultural practices that enable CA systems to succeed.

Beyond these encouragements for technical advances, there is also recognition of the complementary importance of other drivers for change including the requirement for broader education related to improved performance systems and the critical roles

of local farmer knowledge, innovative farmer associations and public policy support for such required advances (Reicosky, 2015). Scaling up the successful adoption of the core soil health management principles and practices of CA systems that have been presented in this chapter throughout the world's irrigated agricultural lands will require, however, region-specific adaptations and options. Challenges to increased adoption by farmers in California's irrigated and historically highly productive Central Valley may require the learning of new production paradigms and mindsets (Mitchell et al., 2016), whereas scaling up CA adoption in developing regions such as Africa may mean creating locally appropriate techniques that avoid both the shortcomings of production models that have been developed and intensively employed in regions such as California (Wright, 2005) and also the indictments recently made of CA as being dogmatic and inflexible (Giller et al., 2015). Franzluebbers (2010) has pointed out that 'monetizing the value of carbon' may also be a necessary aspect of the need for public education on the importance of soil for 'numerous ecosystem services that are currently taken for granted'. Finally, there is recognition of the role of potentially reducing the trend towards meat/animal-based diets in favour of plant-based foods as a future societal goal (Lal, 2013).

8 Where to look for further information

A number of programmes are active worldwide on various aspects of soil health management in arid and semi-arid regions including the internationally affiliated research group of Professor Ken Giller in the Plant Production Systems Department at Wageningen University in the Netherlands (http://www.wur.nl/en/Persons/prof.dr.-KE-Ken-Giller.htm), work in Canada's prairie provinces involving many researchers at or connected with Agriculture & Agri-Food Canada and the Lethbridge Research & Development Centre at the University of Lethbridge (http://www.agr.gc.ca/eng/science-and-innovation/research-centres/alberta/lethbridge-research-and-development-centre/?id=1180547946064), ongoing programmes of Dr. Li Hongwen at the Conservation Tillage Research Center which is part of the Chinese Agricultural University in Beijing (http://caa-ap.org/news/158.html) and the Conservation Agriculture Systems Innovation (CASI) Center in California, US (http://casi.ucanr.edu/). In addition, the Food and Agriculture Organization of the United Nations provides considerable information related to CA (http://222.fao.org/ag/ca/. The Conservation Technology Information Center in Lafayette, IN, USA (http://www.ctic.purdue.edu) has also brought together a group of North American CA groups. Finally, there are a number of organizations in South American countries (e.g. Brazil, Argentina and Paraguay) involved in conservation agriculture, including Aapresid (http://www.aapresid.org.ar/) and CAAPAS (American Confederation of Farmers Organizations toward a Sustainable Agriculture) (http://caapas.org/?reqp=1&reqr=pT5hL25zYzWyqN==). A list of CA associations and links is available at http://www.rolf-derpsch.com/en/links/.

9 References

Alexandratos, N. and J. Bruinsma. 2012. *World Agriculture Towards 2030/2050.* ESA Working Paper No. 12-03. Rome: Agridultural Development Economics Division, FAO. http://www.fao.org/docrep/016/ap106e/ap106e.pdf

Amundson, R., A. A. Berhe, J. W. Hopmans, C. Olson, A. E. Sztein and D. L. Sparks. 2015. Soil and human security in the 21st century. *Science* 348:1261071, p. 6.

Anderson, R. 2011. Synergism: A rotation effect of improved growth efficiency. *Adv. Agron.* 112:205–23.

Barron, J., E. Kemp-Benedict, J. Morris, A. de Bruin, G. Wang and A. Fenci. 2015. Mapping the potential success of agricultural water management for smallholders: Where are the best opportunities? *Water Resour. Rural Develop.* 6:24–49.

Bettner, T. 2012. California roundtable on water and food supply. From storage to retention: Expanding California's options for meeting its water needs, p. 14.

Bouma, J. 2009. Soils are back on the global agenda: Now what? *Geoderma* 150:224–5.

Brauman, K. A., S. Siebert and J. A. Foley. 2013. Improvements in crop water productivity increase water sustainability and food security – A global analysis. *Environ. Res. Lett.* 8:024030, p. 7.

Brennan, E. B. and N. S. Boyd. 2012. Winter cover crop seeding rater and variety effects during eight years of organic vegetables: I. Cover crop biomass production. *Agron. J.* 104:684–90.

Castro Bustamante, S. J. and T. K. Hartz. 2016. Carbon mineralization and water-extractable organic carbon and nitrogen as predictors of soil health and nitrogen mineralization potential. *Comm. Soil Sci. Plant Anal.* 47(Issue Suppl. 1):46–53.

CDFA. 2016. *Healthy Soils Action Plan*. Sacramento, CA: California Department of Food and Agriculture.

Chukalla, A. D., M. S. Krol and A. Y. Hoekstra. 2015. Green and blue water footprint reduction in irrigated agriculture: Effect of irrigation techniques, irrigation strategies and mulching. *Hydrol. Earth Syst. Sci.* 19:4877–91.

Creamer, N. G. and K. R. Baldwin. 2000. An evaluation of summer cover crops for use in vegetable production systems in North Carolina. *HortScience* 35:600–3.

Crovetto, C. 1996. *Stubble over the Soil: The Vital Role of Plant Residue in Soil Management to Improve Soil Quality*. Madison, WI: American Society of Agronomy, p. 241.

Crovetto C. 2006. *No Tillage: The Relationship between No Tillage, Crop Residues, Plants and Soil Nutrition*. Hualpen, Chile: Trama Impresores, p. 216.

DeLaune, P. 2015. Impact of cover crops on Texas rolling plains cotton production. In: *Beltwide Cotton Conference*. 5–7 January 2015. San Antonio, TX: National Cotton Council.

Delgado, J. A., P. M. Groffman, M. A. Nearing, T. Goddard, D. Reicosky, R. Lal, N. R. Kitchen, C. W. Rice, D. Towery and P. Salon. 2011. Conservation practices to mitigate and adapt to climate change. *J. Soil Water Conserv.* 66(4):118A–29A.

Department of Water Resources. 2017. *Reference Evapotranspiration*. California: California Irrigation Management Information System (CIMIS). http://agops.ucr.edu/turf/links/etomap.jpg

FAO. 2017. *Voluntary Guidelines for Sustainable Soil Management*. Rome: Food and Agriculture Organization of the United Nations.

Federoff, N. V., D. S. Battisti, R. N. Beachy, P. J. M. Cooper, D. A. Fishoff, C. N. Hodges, V. C. Reynolds, P. C. Ronald, M. W. Rosegrant, P. A. Sanches, A. Vonshak and J. K. Zhu. 2010. Radically rethinking agriculture for the 21st century. *Science* 327:833–4.

Feger, K.-H. and D. Hawtree. 2013. Soil carbon and water security, pp. 79–99. In: *Ecosystem Services and Carbon Sequestration in the Biosphere*. R. Lal. Dordrecht (Ed), The Netherlands: Springer.

Ferris, H., R. C. Venette and K. M. Scow. 2004. Soil management to enhance bacterivore and fungivore nematode populations and their nitrogen mineralization function. *Appl. Soil Ecol.* 25:19–35.

Foley, J. A., N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, M. Johnston, N. D. Mueller, C. O'Connell, D. K. Ray, P. C. West, C. Balzer, E. M. Bennett, S. R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman and D. P. M. Zaks. 2011. Solutions for a cultivated planet. *Nature* 478:337–42.

Franzluebbers, A. 2010. Will we allow soil carbon to feed our needs? *Carbon Manag.* 1(2):237–51.

Garnett, T., M. C. Appleby, A. Balmford, I. J. Bateman, T. G. Benton, P. Bloomer, B. Burlingame, M. Dawkins, L. Dolan, D. Fraser, M. Herrero, I. Hoffmann, P. Smith, P. K. Thornton, C. Toulmin, S. J. Vermeulen, H. C. J. Godfray. 2013. Sustainable intensification in agriculture: Premises and policies. *Science* 341:33–4.

Giller, K. E., J. A. Andersson, M. Corbeels, J. Kirkegaard, D. Mortensen, O. Erenstein and B. Vanlauwe. 2015. Beyond conservation agriculture. *Front. Plant Sci.* 6:870. 28 October 2015. https://doi.org/10.3389/fpls.2015.00870.

Hall, S. J. 2014. Soils and the future of food. In: *The Soil Underfoot*, pp. 17–35. G. J. Churchman and E. R. Landa (Eds). Boca Ratón, FL: CRC Press.

Hsiao, T. C. 2007. Systematic approach to the improvement of agricultural water use efficiency. In: *Water Use Efficiency and Water Productivity: WASAMED Project*. N. Lamaddalena, M. Shatanawi, M. Todorovic, C. Bogliotti and R. Albrizio Bari (Eds): CIHEAM. http://om/ciheam.org/article.php?IDPDF=800776.

Hudson, B. 1994. Soil water and available water capacity. *J. Soil Water Cons.* 49(2):189–94.

Jägermeyr, J., D. Gerten, S. Schaphoff, J. Heinke, W. Lucht and J. Röckstrom. 2016. Integrated crop management might sustainably halve the global food gap. *Environ. Res. Lett.* 11:025002 (p. 14).

Joyce, B., W. W. Wallender, J. P. Mitchell, L. M. Huyck, S. R. Temple, P. N. Brostrom and T. C. Hsiao. 2002. Infiltration and soil water storage with winter cover cropping. *Trans. Am. Soc. Agric. Eng.* 45:315–26.

Junior, R. C., A. G. de Araujo and R. F. Llanillo. 2012. *No-till Agriculture in Southern Brazil. Factors that Facilitated the Evolution of the System and the Development of the Mechanization of Conservation Farming*. Rome: The Food and Agriculture Organization of the United Nations and the Agricultural Research Institute of Parana State. ISBN: 978-92-5-107102-1.

Karlen, D. L. 2012. Soil health: The concept, its role, and strategies for monitoring. In: *Soil Ecology and Ecosystem Services*, pp. 331–6. D. H. Wall (Ed.). Oxford, UK: Oxford University Press.

Kirkegaard, J. A. and J. R. Hunt. 2010. Increasing productivity by matching farming system management and genotype in water-limited environments. *J. Exp. Bot.* 61(15):4129–43.

Klocke, N. L., R. S. Currie and R. M. Aiken 2009. Soil water evaporation and crop residues. *Trans. ASABE* 52(1):103–10.

Lal, R. 2013. Food security in a changing climate. *Ecohydrol. Hydrobiol.* 13(10):8–21.

Lal, R. 2015. Sequestering carbon and increasing productivity by conservation agriculture. *J. Soil Water Cons.* 70(3):55A–62A.

Larney, F. J. and C. W. Lindwall. 1995. Rotation and tillage effects on available soil water for winter wheat in a semi-arid environment. *Soil Till. Res.* 36:111–27.

Larney, F. J., H. H. Janzen, E. G. Smith and D. W. Anderson. 2004. Dryland agriculture on the Canadian Prairies: Current issues and future challenges. In: *Challenges and Strategies for Dryland Agriculture*. CSSA Special Publication no. 32. Madison, WI: CSSA.

Lindwall, C. W. and B. Sonntag. 2010. *Landscapes Transformed: The History of Conservation Tillage and Direct Seeding*. Canada: Knowledge Impact in Society. ISBN: 978-0-9812843-1-6.

Minoshima, H., L. E. Jackson, T. R. Cavagnaro and H. Ferris. 2007. Short-term fate of carbon-13-depleted cowpea shoots in no-till and standard tillage soils. *Soil Sci. Soc. Am. J.* 71:1859–966.

Mitchell, J. P., D. W. Peters and C. Shennan. 1999. Changes in soil water storage in winter fallowed and cover cropped soils. *J. Sustain. Agri.* 15(2–3):19–31.

Mitchell, J. P., P. N. Singh, W. W. Wallender, D. S. Munk, J. F. Wroble, W. R. Horwath. P. Hogan, R. Roy and B. R. Hanson. 2012. No-tillage and high-residue practices reduce soil water evaporation. *Calif. Ag.* 66, 55–61. April – June 2012.

Mitchell, J. P., A. Shrestha and S. Irmak. 2015a. Tradeoffs between winter crop production and soil water depletion in the San Joaquin Valley. *Calif. J. Soil Water Cons.* 70(6):430–40.

Mitchell, J. P., A. Shrestha, W. R. Horwath, R. J. Southard, N. Madden, J. Veenstra and D. S. Munk. 2015b. Tillage and cover cropping affect crop yields and soil carbon in the San Joaquin Valley, *Calif. Agron. J.* 107(2):588–96.

Mitchell, J., R. Harben, G. Sposito and J. Rossitor 2016. Conservation agriculture: Systems thinking for sustainable farming. *Calif. Agric.*, 70(2):53–6.

Mitchell, J. P., A. Shrestha, K. Mathesius, K. M. Scow, R. J. Southard, R. L. Haney, R. Schmidt, D. S. Munk and W. R. Horwath. 2017. Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California's San Joaquin Valley, USA. *Soil Till. Res.* 165:325–35.

Mosier, A. R., M. A. Bleken, P. Chaiwanakupt, E. C. Freney, R. B. Howarth, P. A. Matson, K. Minami, R. Naylor, K. N. Weeks and Z. L. Zhu. 2002. Policy implications of human-accelerated nitrogen cycling. *Biogeochemistry* 57–58, 477–516.

Palm, C., P. Sánchez, S. Ahamed and A. Awiti. 2007. Soils: A contemporary perspective. *Ann. Rev. Environ. Resour.* 32:99–129.

Paustian, K., J. Lehmann, S. Ogle, D. Reay, G. P. Robertson and P. Smith. 2016. Climate-smart soils. *Nature* 532:49–57.

Pittelkow, C. M., X. Liang, B. A. Linquist, K. J. van Groenigen, J. Lee, M. E. Lundy, N. van Gestel, J. Six, R. T. Venterea and C. van Kessel. 2014. Productivity limits and potentials of the principles of conservation agriculture. *Nature* 517:365–8.

Pittelkow, C., X. Liang, B. Linquist, K. van Groenigen and J. Lee. 2015. Productivity limits and potentials of the principles of Conservation Agriculture. *Nature* 517:365–8.

Poeplau, C. and A. Don. 2015. Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agric. Ecosyst. Environ.* 200:33–41.

Poudel, D. D., W. R. Horwath, J. P. Mitchell and S. R. Temple. 2001. Impacts on cropping systems on soil nitrogen storage and loss. *Agric. Syst.* 68:253–68.

Prichard, T. L., W. M. Wills, W. K. Asai, L. C. Hendricks and C. L. Elmore. 1989. Orchard water use and soil characteristics. *Calif. Ag.* 43, 23–5. July-August.

Rawls, W. J., Y. A. Pachepsky, J. C. Ritchie, T. M. Sobecki and H. Bloodworth. 2003. Effect of soil organic carbon on soil water retention. *Geoderma* 1:61–76.

Reicosky, D. 2003. Conservation agriculture: Global environmental benefits of soil carbon management. In: *Conservation Agriculture*. L. Garcia-Torres, J. Benites, A. Martínez-Vilela and A. Holgado-Cabrera (Eds). Cordoba, Spain: XUL, pp. 3–12.

Reicosky, D. C. 2015. Conservation tillage is not conservation agriculture. *J. Soil Water Cons.* 70(4):103A–8A.

Richter, B. 2016. Water Share. Using water markets and impact investment to drive sustainability. The Nature Conservancy. https://thought-leadership-production.s3.amazonaws.com/2016/08/16/13/41/58/5e9b26b2-5c77-40f6-81fd-03e0c3de78a9/WaterShareReport.pdf

Röckstrom, J. and M. Falkenmark. 2000. Semiarid crop production from a hydrological perspective: Gap between potential and actual yields. *Crit. Rev. Plant Sci.* 19:319–46.

Schipanski, M. E., M. Barbercheck, M. R. Douglas, D. M. Finne, K. Haider, J. P. Kay, A. R. Kemanian, D. A. Mortensen, M. R. Ryan, J. Tooker and C. White. 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agric. Syst.* 125:12–22.

Scott, B. J., C. M. Podmore, H. M. Burns, P. I. Bowden and C. L. McMaster. 2013. *Developments in Stubble Retention in Cropping Systems in Southern Australia*. Orange, New South Wales: Grains Research and Development Corporation, Departtment of Primary Industries, New South Wales Government. https://www.csu.edu.au/__data/assets/pdf_file/0009/922725/Developments-in-Stubble-Retention-in-Cropping-Systems-in-Southern-Australia-11Dec2013.pdf

Smith, E. G., F. J. Larney, D. J. Nakonechny, J. M. Barbieri and C. W. Lindwall. 2012. Productivity of long-term no-till plots – Lethbridge, Alberta. *Prairie Soils Crops J.* 5:123–31.

Snapp, S. S., S. M. Swinton, R. Labarta, D. Mutch, J. R. Black, R. Leep, J. Nyiraneza and K. O'Neil. 2005. Evaluating cover crops for benefits, costs, and performance within cropping system niches. *Agron. J.* 97:322–32.

Sojka, R. H and D. B. Upchurch. 1999. Reservation regarding the soil quality concept. *Soil Sci. Soc. Am. J.* 63:1049–54.

Solomon, S., G. K. Plattner, R. Knutti and P. Friedlingstein. 2009. Irriversible climate change due to carbon dioxide emissions. *PNAS* 106:1704–9. www.pnas.org.cgi.doi/10.1073/pnas.0812721106

Sposito, G. 2013. Green water and global food security. *Vadose Zone J.* 12(4):6.

Sposito, G. 2014. Sustaining 'the genius of soils', pp. 395–408. In: *The Soil Underfoot*. G. J. Churchman and E. R. Landa (Eds). Boca Ratón, FL: CRC Press.

Sposito, G. 2016. *The Chemistry of Soils*. 3rd edition. New York: Oxford University Press.

Stevenson, J. R., R. Serraj and K. G. Cassman. 2014. Evaluating conservation agriculture for small-scale farmers in Sub-Saharan Africa and South Asia. *Agric. Ecosyst. Environ.* 187, 1–10.

Stewart, B. A. and G. A. Peterson. 2015. Managing green water in dryland agriculture. *Agron. J.* 106:1–10.

Swella, G. B., P. R. Ward, K. H. M. Siddique and K. C. Flower. 2015. Combinations of tall standing and horizontal residue affect soil water dynamics in rainfed conservation agriculture systems. *Soil Till. Res.* 147:30–8.

Tilman, D., C. Balzer, J. Hill and B. L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. *Proc. Nat. Acad. Sci.* 108: 20260–4.

van Donk, S. J. Martin, D. L. and Irmak, S. 2010. Crop residue cover effects on evaporation, soil water content, and yield of deficit-irrigated corn in west-central Nebraska. *Trans. ASABE* 53(6):1787–97.

Verburg, K., W. J. Bond and J. R. Hunt. 2012. Fallow management in dryland agriculture: Explaining soil water accumulation using a pulse paradigm. *Field Crops Res.* 130:68–79.

Wall, D. H. (Ed). 2013. *Soil Ecology and Ecosystem Services.* Oxford, UK: Oxford University Press.

Wallace, J. S. 2000. Increasing agricultural water use efficiency to meet future food production. *Agric. Ecosyst. Environ.* 82:105–19.

Wang, L., P. D'Odorico, J. P. Evans, D. J. Eldridge, M. F. Mccabe, K. K. Caylor and E. G. King. 2012. Dryland ecohydrology and climate change: Critical issues and technical advances. *Hydrol. Earth Syst. Sci.* 16:2585–603.

Ward, P. R., K. C. Flower, N. Cordingley, C. Weeks and S. F. Micin. 2012. Soil water balance with cover crops and conservation agriculture in a Mediterranean climate. *Field Crops Res.* 132:33–9.

Weinert, T. L., W. L. Pan, M. R. Moneymaker, G. S. Santo and R. G. Stevens. 2002. Nitrogen recycling by nonleguminous winter cover crops to reduce leaching in potato rotations. *Agron. J.* 94:365–72.

Wright, A. 2005. *The Death of Ramon Gonzalez: The Modern Agricultural Dilemma*. Revised Edition. Austin, TX: University of Texas Press. ISBN-13:978-0292712683.

Wuest, S. B. 2010. Tillage depth and timing effects on soil water profiles in two semiarid soils. *Soil Sci. Soc. Am. J.* 74(5):1701–11.

Wuest, S. B. and W. F. Schillinger. 2011. Evaporation from high residue no-till versus tilled fallow in a dry summer climate. *Soil Sci. Soc. Am. J.* 75(4):1513–19.